



# Non-destructive Evaluation of Self-consolidating High-strength Concrete Incorporating Palm Oil Fuel Ash

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## Authors' contributions

*This work was carried out in collaboration between all authors. Author MS designed the study and guided experimental investigation. Author MAS wrote the first draft of the manuscript and managed literature searches. Authors MS and MAS managed the analyses of the study. All authors read and approved the final manuscript.*

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## ABSTRACT

This paper presents the results of the key non-destructive tests performed on the self-consolidating high-strength concrete (SCHSC) mixes including palm oil fuel ash (POFA) as a pozzolanic supplementary cementing material. Twenty (20) SCHSC mixes were produced with several water-to-binder (W/B) ratios ranging from 0.25 to 0.40. POFA was incorporated in concrete mixes substituting 0%, 10%, 20%, 25% and 30% of ordinary portland cement (OPC) by weight. The non-destructive tests were carried out to determine the dynamic modulus of elasticity and ultrasonic pulse velocity (UPV) of the concretes. In addition, the 28 and 56 days compressive strengths were determined to verify whether the concretes possessed high strength or not. The slump flow of the

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concrete mixes was also investigated to observe their self-consolidation capacity. Nevertheless, more emphasis was given to observe the effects of W/B ratio and POFA content on the selected non-destructive properties of the concretes. Moreover, the correlations of UPV and dynamic modulus of elasticity with compressive strength were determined. The concrete mixes produced had the required slump flow values ( $\geq 600$  mm) for self-consolidating concrete. The compressive strength of all concretes satisfied the strength requirement ( $\geq 50$  MPa) of high-strength concrete for all replacement levels of OPC. The UPV and dynamic elasticity decreased with higher W/B ratio. POFA was effective in improving the non-destructive properties of concretes up to 20% replacement of cement by weight. Hence, the optimum POFA content was 20% in the context of the present study. Furthermore, the dynamic modulus of elasticity and UPV were strongly correlated with the compressive strength of SCHSC possessing a correlation coefficient of +0.9413 and +0.9709, respectively.

**Keywords:** *Compressive strength; dynamic modulus of elasticity; palm oil fuel ash (POFA); self-consolidating high-strength concrete (SCHSC); slump flow; ultrasonic pulse velocity (UPV); water-to-binder (W/B) ratio.*

## 1. INTRODUCTION

Non-destructive testing (NDT) is carried out as a part of the detailed investigation for concrete properties to complement the destructive test methods. Several NDT methods have been developed for assessment of concrete properties. These test methods do not require destruction of concrete elements or specimens. In addition, NDT methods are useful to establish correlations between the strength and non-destructive properties of concrete [1]. These correlations can be used indirectly to examine the strength properties of concrete without involving any destructive tests [2].

Carino [3] summarized the use of different NDT methods and discussed the challenges for the 21<sup>st</sup> century. He provided a historical perspective on the development of NDT methods for concrete and outlined future directions. Rajagopalan et al. [4] reported a correlation between the compressive strength and ultrasonic pulse velocity (UPV) for several typical mixes of concrete. They concluded that UPV tests at the age of 7 days are more reliable than 28 days for assessing compressive strength. Anderson and Seals [5] performed experiments using dynamic NDT procedures to predict the long-term compressive strength of in-situ concrete from its UPV. They concluded that UPV measurements can be used for a comprehensive evaluation of in-situ strength. Mehta and Monteiro [6] determined the dynamic modulus of elasticity of low-, medium-, and high-strength concretes and correlated with the static modulus of elasticity of concrete. Their study revealed that the dynamic modulus of elasticity are generally 20%, 30%, and 40% higher than the static modulus of

elasticity for high-, medium-, and low-strength concretes, respectively. Al-Amoudi et al. [7] determined the compressive strength and UPV of concrete incorporating fly ash as a supplementary cementing material (SCM) and established a correlation between them. They observed good correlation between compressive strength and UPV. Raman et al. [8] investigated NDT properties such as UPV, dynamic modulus of elasticity, and initial surface absorption; they correlated these properties with the compressive strength of flowing concrete including quarry waste as a partial replacement of mining sand. They found that dynamic modulus of elasticity, UPV, and initial surface absorption varied linearly with compressive strength. Shariati et al. [1] performed experimental studies on in-situ concrete in existing buildings using PUNDIT (Portable Ultrasonic Non-destructive Digital Indicating Tester) and Schmidt rebound hammer; they established the correlations of compressive strength with UPV and rebound number. Their predicted compressive strength obtained from the correlations was very closer to the experimental compressive strength. Safiuddin et al. [9] investigated the compressive strength, UPV, and electrical resistivity of self-consolidating high-performance concrete incorporating rice husk ash (RHA) as a pozzolanic SCM. They observed that RHA can significantly improve the strength and non-destructive properties of concrete. However, limited research has been carried out on the non-destructive properties of self-consolidating high-strength concrete (SCHSC) incorporating palm oil fuel ash (POFA).

POFA is a waste material produced after the extraction of oil from the fresh fruit bunches of oil

palm tree. This ash is mostly dumped in open field near palm oil mills without any profitable return, thus causing environmental pollution and health hazard [10,11]. It has been found that the properly processed POFA can be used successfully as a pozzolanic SCM to produce various types of concrete [12]. The use of POFA in concrete contributes to enhance the quality of concrete with respect to strength and non-destructive properties due to its microfilling ability and pozzolanic activity [13,14].

The main objective of this study was to investigate the non-destructive properties of SCHSC and to examine their correlations with compressive strength. Twenty (20) SCHSC mixes were produced with several water-to-binder (W/B) ratios ranging from 0.25 to 0.40. POFA was incorporated in the concrete mixes substituting 0%, 10%, 20%, 25% and 30% of ordinary portland cement (OPC) by weight. Two key non-destructive properties such as UPV and dynamic modulus of elasticity as well as the compressive strength of SCHSC mixes were determined. The slump flow of the fresh concrete mixes was also measured to observe the self-consolidation capacity of concrete.

## 2. EXPERIMENTAL DETAILS

### 2.1 Materials

The coarse aggregate (CA) used in this study was locally available crushed granite stone whereas the fine aggregate (FA) used was the sand obtained from a local mine. The ordinary (ASTM Type I) portland cement (OPC) was used as the main cementing material. POFA was used as a pozzolanic SCM substituting 0–30% of OPC. POFA was collected from Jugra Palm Oil

Mill located in Banting, Selangor, Malaysia. It was obtained at 800–1000°C and processed through proper grinding to provide a fineness greater than that of OPC. POFA and OPC together acted as the binder (B). The mixing water (W) used was normal tap water. A polycarboxylate based high-range water reducer (HRWR) was also used in the present study to achieve the self-consolidation capacity of concrete.

Constituent materials were tested to verify their suitability and to facilitate mix proportioning of concrete mixes. CA and FA were tested to determine their specific gravity, water absorption, bulk density, moisture content, and gradation. POFA and OPC were tested for their specific gravity, particle size distribution, sieve fineness, specific surface area, and chemical composition. POFA was also tested for its pozzolanic activity index. The particle size distributions of OPC and POFA were determined by the laser diffraction method. The chemical compositions of POFA and OPC were obtained using the X-ray fluorescence (XRF) method. The HRWR was tested for its specific gravity and solid content. The physical properties CA, FA, OPC, POFA and HRWR are given in Table 1. The gradations of CA and FA are shown in Fig. 1. The particle size distributions of POFA and OPC are shown in Fig. 2. The chemical compositions of OPC and POFA are presented in Table 2.

### 2.2 Mix Proportions of Concrete

Twenty (20) SCHSC mixes were prepared with the W/B ratios of 0.25, 0.30, 0.35, and 0.40. POFA was incorporated in the concrete mixes replacing 0%, 10%, 20%, 25%, and 30% of OPC by weight.

**Table 1. Properties of constituent materials**

| Properties   | CA   | FA   | OPC  | POFA | HRWR |
|--|------|------|------|------|------|
| Relative density   | 2.62 | 2.69 | 3.16 | 2.48 | 1.05 |
| Median particle size, $d_{50}$ ( $\mu\text{m}$ )         | -    | -    | 14.6 | 9.5  | -    |
| % passing through 45- $\mu\text{m}$ sieve (% mass)       | -    | -    | 91.5 | 95   | -    |
| Specific surface area, Blaine ( $\text{m}^2/\text{kg}$ ) | -    | -    | 351  | 775  | -    |
| Specific surface area, BET ( $\text{m}^2/\text{kg}$ )    | -    | -    | 3046 | 4103 | -    |
| Pozzolanic activity index (28 days) (%)                  | -    | -    | -    | 105  | -    |
| Solid content (%)  | -    | -    | -    | -    | 30   |
| Absorption capacity (%)                                  | 0.55 | 1.32 | -    | -    | -    |
| Moisture content (%)                                     | 0.27 | 0.31 | -    | -    | -    |
| Fineness modulus   | 6.76 | 2.88 | -    | -    | -    |
| Bulk density (oven-dry) ( $\text{kg}/\text{m}^3$ )       | 1515 | 1700 | -    | -    | -    |
| Co-efficient of gradation                                | 1.11 | 1.05 | -    | -    | -    |

The water content for the SCHSC mixes was selected based on the guidelines given in ACI 211.4R-08 [15] whereas the amount of cement was calculated based on the selected W/B ratios. The optimum fine aggregate/total aggregate (FA/TA) ratio was determined based on the maximum bulk density of aggregate blends and it was 0.50 for all SCHSC mixes. The HRWR dosages were fixed based on trial mixes to

ensure the self-consolidation capacity of concrete with a slump flow in the range of 600–800 mm. The detailed mix proportions for various SCHSC mixes are given in Table 3. The SCHSC mixes were designated based on their W/B ratio and POFA content. For example, C25P10 implies an SCHSC mix whose W/B ratio and POFA content was 0.25 and 10%, respectively.

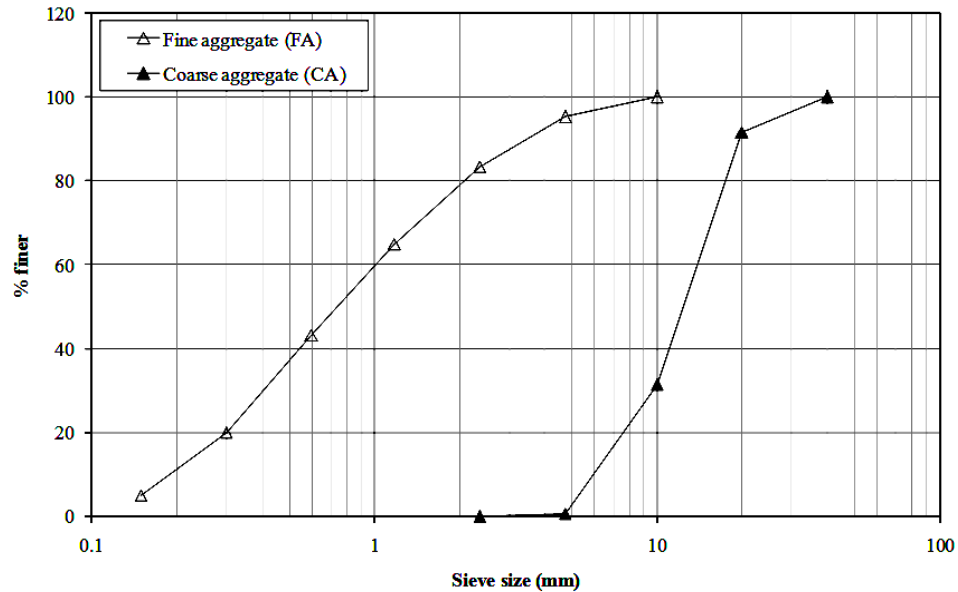


Fig. 1. Gradations of coarse and fine aggregates

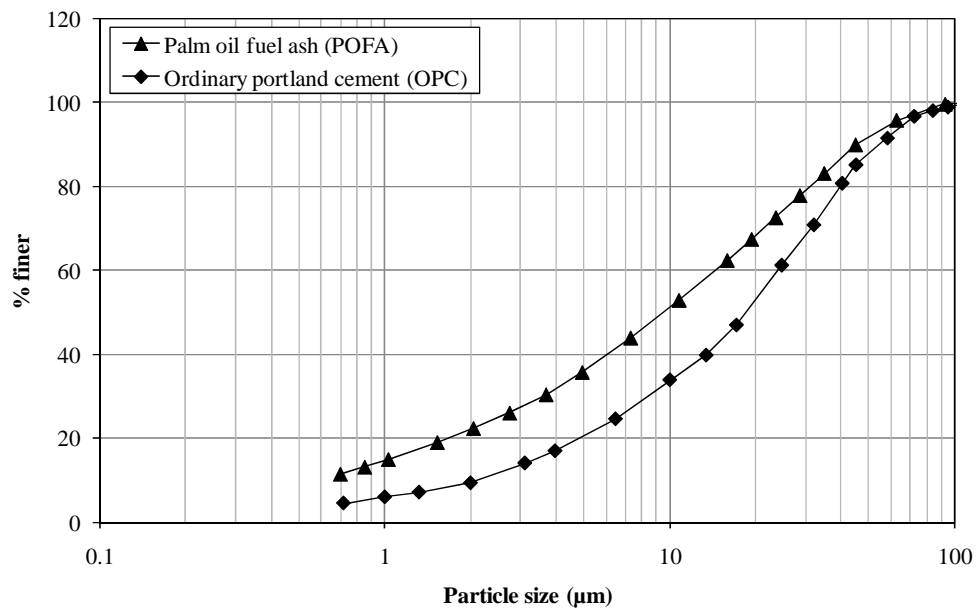


Fig. 2. Particle size distributions of OPC and POFA

**Table 2. Chemical compositions of OPC and POFA**

| Chemical component             | Quantity (% by mass) |       |
|--------------------------------|----------------------|-------|
|                                | OPC                  | POFA  |
| CaO                            | 71.79                | 4.89  |
| SiO <sub>2</sub>               | 15.20                | 62.27 |
| Al <sub>2</sub> O <sub>3</sub> | 3.44                 | 3.18  |
| Fe <sub>2</sub> O <sub>3</sub> | 2.88                 | 13.57 |
| P <sub>2</sub> O <sub>5</sub>  | 0.40                 | 3.64  |
| SO <sub>3</sub>                | 3.91                 | 0.36  |
| K <sub>2</sub> O               | 0.40                 | 7.89  |
| MgO                            | 1.70                 | 3.67  |
| TiO <sub>2</sub>               | 0.13                 | 0.17  |
| MnO                            | 0.07                 | 0.16  |
| CuO                            | -                    | 0.09  |
| ZnO                            | -                    | 0.03  |
| Rb <sub>2</sub> O              | -                    | 0.04  |
| SrO                            | 0.03                 | -     |

**Table 3. Mix proportions of different concrete mixes**

| Concrete type | W/B ratio | CA                   | FA                   | OPC                  | POFA  |                      | W                    | HRWR  |
|---------------|-----------|----------------------|----------------------|----------------------|-------|----------------------|----------------------|-------|
|               |           | (kg/m <sup>3</sup> ) | (kg/m <sup>3</sup> ) | (kg/m <sup>3</sup> ) | (% B) | (kg/m <sup>3</sup> ) | (kg/m <sup>3</sup> ) | (% B) |
| C25P0         | 0.25      | 780.0                | 779.7                | 705.9                | 0     | 0                    | 176.5                | 1.8   |
| C25P10        | 0.25      | 772.0                | 771.4                | 635.3                | 10    | 70.6                 | 176.5                | 1.845 |
| C25P20        | 0.25      | 763.0                | 761.0                | 564.7                | 20    | 141.2                | 176.5                | 1.875 |
| C25P25        | 0.25      | 758.0                | 757.9                | 529.4                | 25    | 176.5                | 176.5                | 2     |
| C25P30        | 0.25      | 754.0                | 752.1                | 494.1                | 30    | 211.8                | 176.5                | 2.1   |
| C30P0         | 0.30      | 834.0                | 833.2                | 588.2                | 0     | 0                    | 176.5                | 1.5   |
| C30P10        | 0.30      | 827.0                | 825.6                | 529.4                | 10    | 58.8                 | 176.5                | 1.575 |
| C30P20        | 0.30      | 819.0                | 817.1                | 470.6                | 20    | 117.6                | 176.5                | 1.8   |
| C30P25        | 0.30      | 815.0                | 813.3                | 441.2                | 25    | 147.1                | 176.5                | 1.875 |
| C30P30        | 0.30      | 811.0                | 809.9                | 411.8                | 30    | 176.5                | 176.5                | 1.925 |
| C35P0         | 0.35      | 872.0                | 871.4                | 504.2                | 0     | 0                    | 176.5                | 1.2   |
| C35P10        | 0.35      | 867.0                | 865.3                | 453.8                | 10    | 50.4                 | 176.5                | 1.225 |
| C35P20        | 0.35      | 860.0                | 858.5                | 403.4                | 20    | 100.8                | 176.5                | 1.25  |
| C35P25        | 0.35      | 856.0                | 855.5                | 378.2                | 25    | 126.1                | 176.5                | 1.5   |
| C35P30        | 0.35      | 853.0                | 851.9                | 352.9                | 30    | 153.3                | 176.5                | 1.575 |
| C40P0         | 0.40      | 901.0                | 899.5                | 441.2                | 0     | 0                    | 176.5                | 1.0   |
| C40P10        | 0.40      | 895.0                | 894.9                | 397.1                | 10    | 44.1                 | 176.5                | 1.05  |
| C40P20        | 0.40      | 890.0                | 888.2                | 352.9                | 20    | 88.2                 | 176.5                | 1.2   |
| C40P25        | 0.40      | 887.0                | 885.9                | 330.9                | 25    | 110.3                | 176.5                | 1.225 |
| C40P30        | 0.40      | 884.0                | 882.1                | 308.8                | 30    | 132.4                | 176.5                | 1.4   |

### 2.3 Preparation and Testing of Concretes

The fresh SCHSC mixes were prepared in accordance with the mixing procedure described by Safiuddin [16]. Immediately after the completion of mixing, the slump flow of the fresh concretes was determined to examine their self-consolidation capacity. The slump flow was determined according to ASTM C 1611/C 1611M-09a [17].

The cylinder specimens of Ø100×200H mm were fabricated for the compressive strength and UPV

tests of different SCHSCs. In addition, 100W×100H×500L mm prisms were fabricated for the dynamic modulus of elasticity test of the concretes. Upon completion of casting, the specimens were left undisturbed and covered with plastic sheet and wet burlap to avoid evaporation. The specimens were de-moulded, marked, and transferred to the curing tank for wet curing at the age of 24±4 h. The curing temperature was 23±2°C. The wet curing was continued until the day of testing. The compressive strength of various SCHSCs was determined at the ages of 28 and 56 days by

testing triplicate Ø100x200H mm cylinder specimens according to ASTM C 39/ C 39M [18]. The dynamic modulus of elasticity of different SCHSCs was determined by measuring the fundamental resonant frequency of concrete in accordance with ASTM C 215 [19]. The test was carried out at the ages of 28 and 56 days using 100Wx100Hx500L mm concrete prisms. A resonant frequency tester was used to perform the test. The UPV of various SCHSCs was determined following ASTM C 597 [20]. The test was performed at the ages of 28 and 56 days using Ø100x200H mm concrete cylinders. A PUNDIT Plus was used for determining the UPV of the concretes.

### 3. RESULTS AND DISCUSSION

#### 3.1 Workability

The workability of SCHSC was measured with respect to slump flow. In this study, the slump flow varied in the range of 605–720 mm as shown in Table 4. The slump flow results revealed that the concretes were highly workable and had the self-consolidation capacity as they provided a slump flow greater than 600 mm. The slump flow for self-consolidating concrete varies in the range of 600-800 mm [21]. In the present study, adequate HRWR dosage and required cement content were used to obtain the self-consolidation capacity of the concretes. An appropriate HRWR dosage and a proper paste volume at relatively high cement content improve the deformability of SCHSC and thus result in a greater slump flow [16,22].

#### 3.2 Compressive Strength

The average compressive strengths of different SCHSCs (obtained by testing triplicate Ø100x200H mm cylinders) at 28 and 56 days are shown in Table 4. The variation between the average strength and each cylinder strength was less than 10%. The 28 days compressive strength varied from 52.3 to 74.2 MPa while the 56 days compressive strength differed from 54.8 to 77.0 MPa. These results revealed that the concretes produced were high-strength concrete. The minimum 28-day compressive strength requirement for high-strength concrete is 50 MPa [23]; this requirement was fulfilled by all SCHSC mixes produced in the present study. The compressive strength increased with lower W/B ratio (refer to Table 3 and Table 4). It is well known in concrete technology that a decrease in W/B ratio increases the compressive strength of concrete [24]. This is because the microstructure

of concrete is significantly improved at a lower W/B ratio due to reduced quantity of water or increased amount of binder. In the present study, the binder content increased with lower W/B ratio as the amount of water was kept constant (refer to Table 3). Therefore, an increased amount of hydration products was produced from the hydration of cement. As a result, the porosity was significantly decreased, the microstructure was improved, and the concrete possessed a higher compressive strength. These findings were previously published by the authors [25,26].

The POFA content influenced the compressive strength of concrete. It is obvious from Table 4 that the compressive strength of concretes increased with the increase in POFA content up to 20%, which resulted in the maximum strength gain. Similar results were observed by other researchers. According to Sata et al. [27], the optimum ground POFA content was 20% that provided the highest level of concrete strength. Also, Chindapasirt et al. [28] found that the compressive strength of concrete with 20% ground POFA was higher than that of OPC concrete. The compressive strength of the concretes including up to 20% POFA increased due to the effective pozzolanic behaviour of POFA particles. This can be justified based on the pozzolanic activity index of POFA. In the present study, the pozzolanic activity index of POFA was 105% (Table 1); it is substantially higher than the minimum limit of 75% for SCM, as specified in ASTM C 618-08a [29]. The high SiO<sub>2</sub> content (62.3%) of the ground POFA (refer to Table 2) reacted with Ca(OH)<sub>2</sub> (liberated from cement hydration) to produce additional calcium silicate hydrate (secondary C-S-H), which improved the compressive strength of concrete. Furthermore, POFA had a higher surface area due to smaller particle size (refer to Table 1 and Fig. 2), and therefore enhanced the pozzolanic activity and hence the compressive strength of concrete. The microfilling ability of POFA also contributed to increase the compressive strength of SCHSC. The median particle size of POFA was lower than that of OPC (refer to Table 1 and Fig. 2). The finer POFA particles filled in the micro-voids within the cement paste due to smaller particle size and thus improved the compressive strength of concrete producing a dense microstructure.

POFA was not effective in increasing the compressive strength of concrete when used with an amount more than 20% replacement of cement. Beyond this replacement level, a

**Table 4. Fresh and hardened properties of SCHSCs**

| Concrete type | Slump flow (mm) | Compressive strength (MPa) |         | Dynamic modulus of elasticity (GPa) |         | Ultrasonic pulse velocity (km/s) |         |
|---------------|-----------------|----------------------------|---------|-------------------------------------|---------|----------------------------------|---------|
|               |                 | 28 days                    | 56 days | 28 days                             | 56 days | 28 days                          | 56 days |
| C25P0         | 660             | 70.9                       | 72.9    | 43.08                               | 44.60   | 4.74                             | 4.76    |
| C25P10        | 680             | 72.9                       | 75.5    | 43.71                               | 45.35   | 4.76                             | 4.79    |
| C25P20        | 705             | 74.2                       | 77.0    | 45.21                               | 47.09   | 4.8                              | 4.85    |
| C25P25        | 710             | 68.2                       | 70.8    | 42.59                               | 44.27   | 4.75                             | 4.78    |
| C25P30        | 720             | 65.9                       | 68.4    | 41.20                               | 42.69   | 4.72                             | 4.75    |
| C30P0         | 640             | 67.6                       | 69.5    | 41.86                               | 43.16   | 4.7                              | 4.72    |
| C30P10        | 655             | 69.3                       | 72.1    | 42.29                               | 44.19   | 4.72                             | 4.75    |
| C30P20        | 670             | 71.3                       | 74.1    | 44.41                               | 46.51   | 4.75                             | 4.8     |
| C30P25        | 680             | 65.5                       | 68.1    | 41.08                               | 43.02   | 4.7                              | 4.74    |
| C30P30        | 700             | 63.1                       | 65.6    | 40.45                               | 42.28   | 4.68                             | 4.71    |
| C35P0         | 630             | 61.4                       | 63.2    | 39.81                               | 41.22   | 4.64                             | 4.67    |
| C35P10        | 640             | 62.8                       | 65.5    | 41.08                               | 42.61   | 4.66                             | 4.71    |
| C35P20        | 665             | 64.2                       | 66.9    | 42.33                               | 44.05   | 4.68                             | 4.76    |
| C35P25        | 670             | 58.8                       | 61.6    | 39.85                               | 41.72   | 4.63                             | 4.68    |
| C35P30        | 675             | 57.7                       | 60.3    | 38.71                               | 40.51   | 4.6                              | 4.63    |
| C40P0         | 605             | 56.2                       | 58.0    | 39.01                               | 40.08   | 4.57                             | 4.6     |
| C40P10        | 620             | 57.9                       | 60.2    | 39.82                               | 41.47   | 4.6                              | 4.64    |
| C40P20        | 630             | 58.2                       | 60.8    | 40.31                               | 42.08   | 4.63                             | 4.68    |
| C40P25        | 635             | 54.1                       | 56.8    | 38.56                               | 40.10   | 4.58                             | 4.61    |
| C40P30        | 645             | 52.3                       | 54.8    | 37.79                               | 39.16   | 4.55                             | 4.58    |

gradual reduction in compressive strength was observed (refer to Table 4). When used as 25% replacement of cement, POFA decreased the compressive strength of concrete by 2-3%. More reduction in compressive strength occurred for further increase in POFA content. A 5-7% reduction in compressive strength occurred when 30% POFA was used in concrete. Indeed, the lowest level of compressive strength at all ages was achieved for 30% POFA, as evident from Table 4. These findings indicate that the incorporation of POFA at a content higher than 20% significantly decreased the amount of cement in concrete. Consequently, the amount of the strength-contributing hydration product (primary C-S-H) obtained from cement hydration was reduced. Furthermore, a relatively small amount of  $\text{Ca(OH)}_2$  was liberated from cement hydration. Hence, a lower quantity of secondary C-S-H was obtained from the pozzolanic reaction between POFA and  $\text{Ca(OH)}_2$ . This suggests that the pozzolanic activity and microfilling ability of POFA could not compensate the loss of compressive strength due to more than 20% reduction in cement content.

### 3.3 Dynamic Modulus of Elasticity

The average dynamic modulus of elasticity of various SCHSCs (obtained by testing 100W×100H×500L mm concrete prisms) at 28

and 56 days are given in Table 4. The variation between the average and individual dynamic modulus of elasticity values was less than 5%. The dynamic modulus of elasticity varied from 37.79 GPa to 47.09 GPa. The dynamic modulus of elasticity of SCHSC decreased with the increased W/B ratio, as obvious from Fig. 3. In the present study, the aggregate content slightly increased and the paste volume significantly decreased with higher W/B ratio for the same volume of SCHSC mixes, as evident from Table 3. Hence, it was expected that the dynamic modulus of elasticity might increase with higher W/B ratio. Generally, the modulus of elasticity increases with higher aggregate content and lower paste volume [30]. However, the higher modulus of elasticity can be obtained in the case of SCHSC due to the denser packing of the particles, despite higher paste volume or lower aggregate content [31]. Therefore, the SCHSC mix with a lower W/B ratio had a higher dynamic modulus of elasticity in the present study. The high workability (refer to slump flow results shown in Table 4) resulting from adequate HRWR dosage and relatively high binder content (refer to Table 3), that is, high paste volume contributed to produce a denser microstructure in such SCHSC.

POFA influenced the dynamic modulus of elasticity of SCHSC. In this study, the SCHSC

incorporating 20% POFA had a higher dynamic modulus of elasticity than the control concrete (0% POFA), as evident from Fig. 3. The maximum increase in the dynamic modulus of elasticity of the concrete including 20% POFA was about 6% and 8% at 28 and 56 days, respectively, as compared with the control concrete. This is mainly due to the improvement of microstructure in bulk cement paste, and interfacial transition zone between aggregate and cement paste caused by the microfilling ability and pozzolanic activity of ground POFA [32]. In a complementary research, the authors of the present study also observed the improvement of microstructure in bulk cement paste and interfacial transition zone through a scanning electron microscope [26]. Furthermore, the dynamic modulus of elasticity of the concrete incorporating 25% POFA was comparable to that of the control concrete; however, the modulus of elasticity of the concrete including 30% POFA was lower than that of the control concrete due to the same reasons as discussed earlier in the case of compressive strength.

### 3.4 Ultrasonic Pulse Velocity (UPV)

The UPV results of the SCHSCs (obtained by testing triplicate  $\varnothing 100 \times 200$  mm cylinders) at 28 and 56 days are presented in Table 4. The variation between the average and individual ultrasonic pulse velocity values was less than 5%. The UPV varied in the range of 4.55–4.85 km/s, thus the concretes produced in this study can be categorized as “excellent concrete”. This is because a concrete possessing a UPV higher

than 4.5 km/s is generally classified as a concrete with excellent quality [24]. The quality of SCHSCs was excellent mostly due to the compact pore structure of concrete. Similar results were obtained by Lin et al. [33].

The UPV of the SCHSCs increased with lower W/B ratio, as evident from Fig. 4. The concretes produced with the W/B ratio of 0.25 provided the highest level of UPV. On the contrary, the concretes produced with the W/B ratio of 0.40 provided the lowest level of UPV. However, the UPV values obtained for this W/B ratio (0.40) still represented the excellent physical quality of concrete. This is due to the reason that the aggregate content increased at higher W/B ratio, as obvious from Table 3. The higher aggregate content accelerates the propagation of the pulse through concrete and therefore the UPV is increased for the same strength level [34,35].

POFA influenced the UPV of SCHSCs, as evident from Fig. 4. The presence of POFA was effective in improving the UPV of the concretes. The maximum UPV was obtained for the concrete including 20% POFA. This is because 20% POFA contributed to pore refinement in SCHSC leading to a dense microstructure that enhanced the UPV of concrete. The UPV of the SCHSC at 25% POFA was very close to that of the control concrete. However, a reduction in UPV was observed for 30% POFA due to the same reasons as discussed earlier in the cases of compressive strength and dynamic modulus of elasticity.

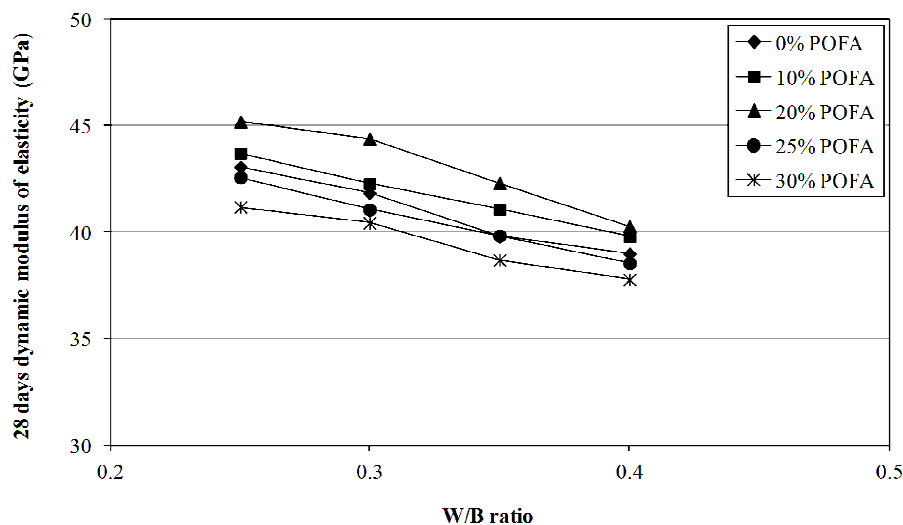


Fig. 3. Effects of W/B ratio and POFA content on the dynamic modulus of elasticity of SCHSC



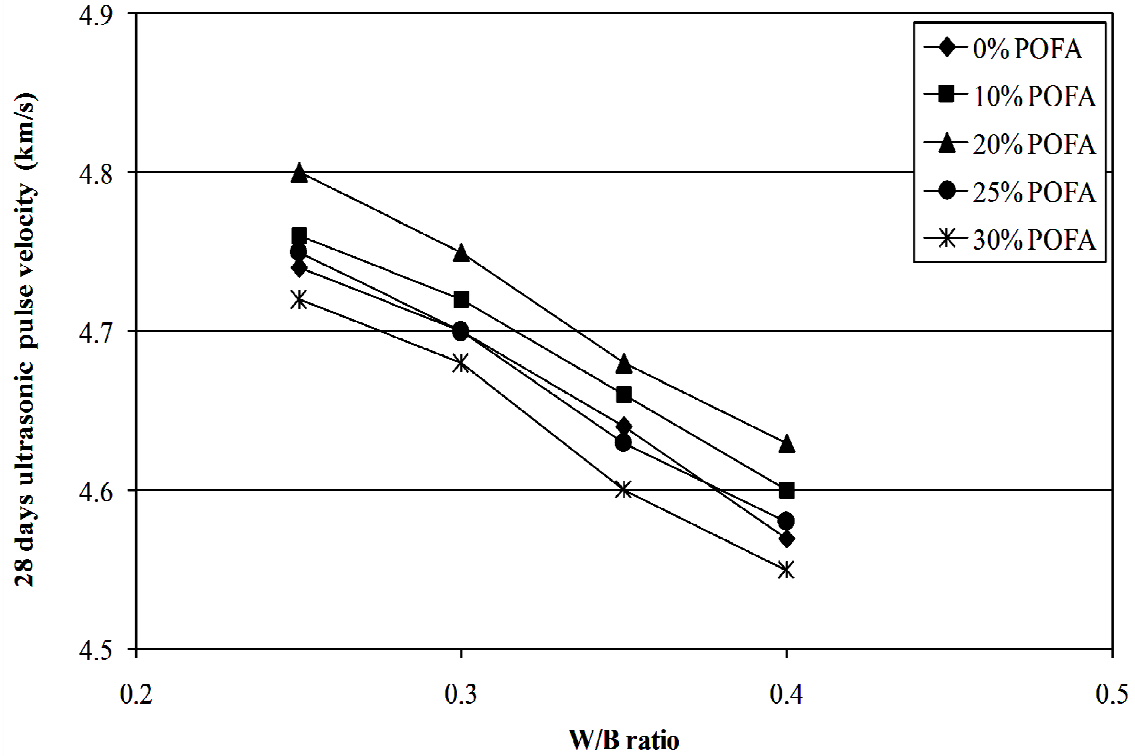


Fig. 4. Effects of W/B ratio and POFA content on the ultrasonic pulse velocity of SCHSC

### 3.5 Correlations between Non-destructive Properties and Strength of SCHSC

#### 3.5.1 Dynamic modulus of elasticity and compressive strength

The dynamic modulus of elasticity of SCHSC was strongly correlated with its square root of compressive strength possessing a positive linear relationship, as shown in Fig. 5. The relationship is represented by:

$$E_d = 5.2186 (\sqrt{f'_c}) - \dots \quad (1)$$

The relationship shown in Equation (1) is valid for the compressive strength ranging from 52.3 MPa to 76.6 MPa and the dynamic modulus of elasticity ranging from 37.79 GPa to 47.09 GPa. The correlation coefficient ( $r$ ) for the dynamic modulus of elasticity and compressive strength of different SCHSCs is +0.9413, which expresses a strong positive relationship. The excellent correlation was observed because both compressive strength and dynamic modulus of elasticity varied similarly with the W/B ratio and POFA content of SCHSC. A similar correlation

was observed by Raman et al. [8] in their study on flowing concrete including quarry waste.

#### 3.5.2 Ultrasonic pulse velocity (UPV) and compressive strength

The correlation between the compressive strength and UPV of SCHSC is shown in Fig. 6. The correlation is represented by:

$$f'_c = 85.723 (V_{up}) - 337.33 - \dots \quad (2)$$

The relationship represented by Equation (2) is valid for the UPV varying from 4.55 km/s to 4.86 km/s and the compressive strength ranging from 52.3 MPa to 76.6 MPa. In the present study, both compressive strength and UPV varied similarly with the W/B ratio and POFA content of SCHSC. Therefore, a strong positive linear relationship with a correlation coefficient ( $r$ ) of +0.9709 was observed for the compressive strength and UPV of SCHSC mixes incorporating POFA. A strong correlation between compressive strength and UPV was also observed by Demirboğa et al. [36] for the concretes including fly ash and slag, and by Safiuddin [16] for the concretes incorporating rice husk ash.

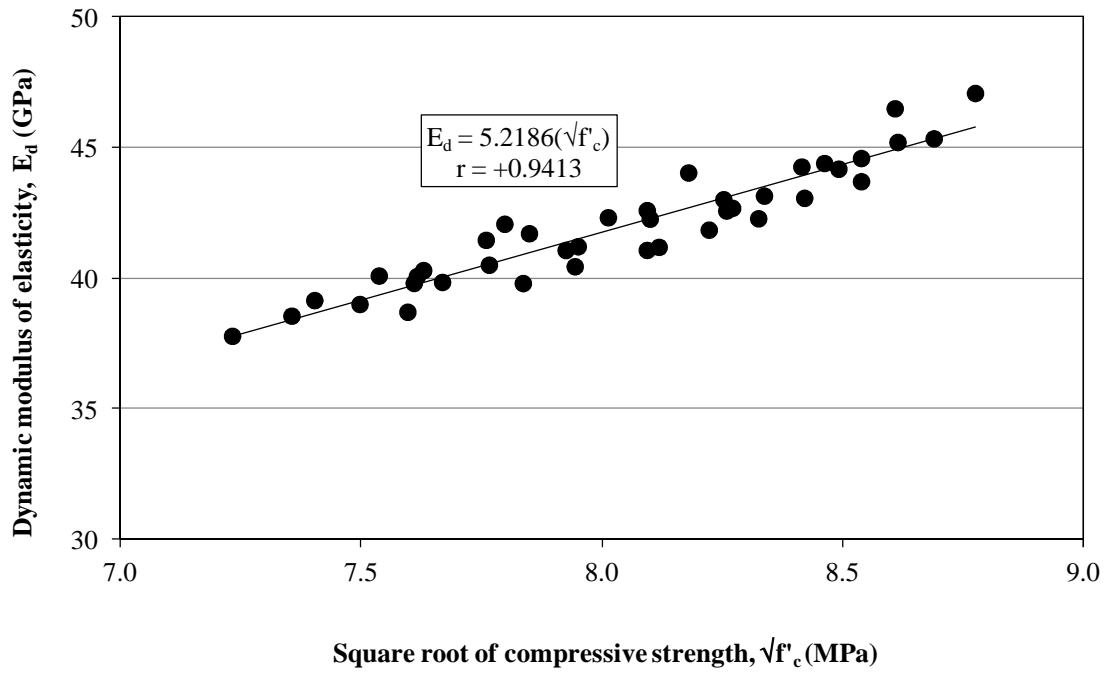


Fig. 5. Correlation between compressive strength and dynamic modulus of elasticity of SCHSC

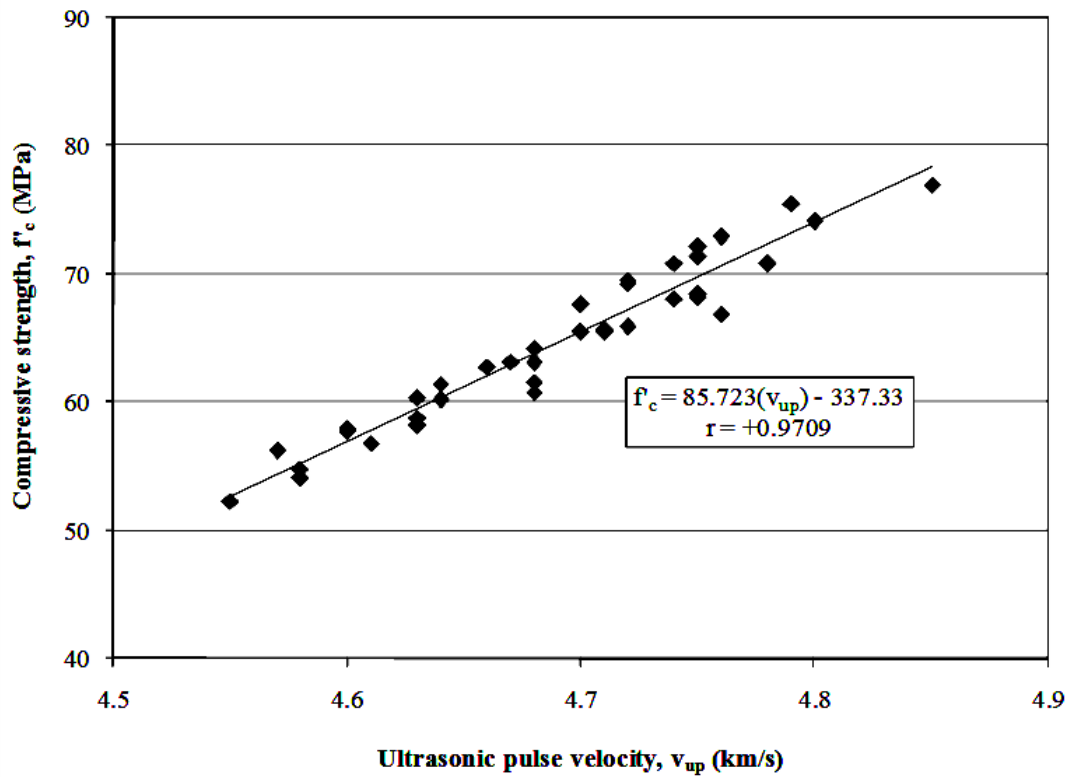


Fig. 6. Correlation between compressive strength and ultrasonic pulse velocity of SCHSC

#### 4. CONCLUSIONS

The overall research findings of the present study regarding SCHSC with POFA are concluded below.

- 1) The concretes fulfilled the workability (slump flow) requirement for self-consolidating concrete. All concretes had a good self-consolidation capacity as they possessed a slump flow greater than 600 mm.
- 2) The concretes provided a compressive strength in the range of 52-77 MPa and thus fulfilled the minimum strength requirement for high-strength concrete.
- 3) POFA produced a significant effect on the key non-destructive properties (dynamic modulus of elasticity and UPV) of SCHSC. The non-destructive properties of SCHSC were improved in the presence of POFA up to 20% replacement of OPC. This is mostly credited to the pozzolanic activity of POFA. The fineness of POFA also played an important role to enhance the aforementioned non-destructive properties of concrete. The high fineness of POFA improved its microfilling ability and pozzolanic activity, and thus contributed to improve the non-destructive properties of concrete.
- 4) The key non-destructive properties (dynamic modulus of elasticity and UPV) of SCHSC were improved with lower W/B ratio. The lower W/B ratio was associated with higher binder content, which produced greater hydration products and thus resulted in enhanced paste densification leading to a compact microstructure or pore structure.
- 5) The highest compressive strength was achieved for the SCHSC incorporating 20% POFA. This finding is consistent with the non-destructive properties of SCHSC including 20% POFA.
- 6) Strong correlations were observed between the compressive strength and non-destructive properties (dynamic modulus of elasticity and UPV) of SCHSC. This is due to their similar variations with the W/B ratio and POFA content of concrete.

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#### COMPETING INTERESTS

Authors have declared that no competing interests exist.

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