The Compressive Strength and Water Absorption of Railway’s Concrete Sleepers Containing Palm Oil Fuel Ash (POFA) as a Cement Replacement Material

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Abstract. Railway’s concrete sleepers demand high consumption of cement which generates higher energy assumption and carbon emission. Meanwhile, in Malaysia, around 100 tonnes of palm oil fuel ash (POFA) were disposed of in the landfill, which endangering environmental health. However, this POFA have pozzolanic properties that can be employed as cementitious material. Therefore, this study aimed to produce a sustainable concrete sleeper by using POFA as a cement replacement material focusing on the compressive strength and water absorption performance. Concrete samples with a strength grade of 55MPa and w/c of 0.35 were prepared with three design mixes containing 0% (control), 20%(POFA20), and 40%(POFA40) of POFA. For the compressive strength test, a compression machine was used. Meanwhile, the water absorption was measured at atmospheric pressure. Both tests were conducted at 7 and 28 days of curing age. The results show that as the curing age increases, their water absorption and compressive strength improves, indicating a pozzolanic reaction. In terms of POFA content, the water absorption increases by 14% and 54% for POFA20 and POFA40, respectively. Meanwhile, the compressive strength reduced by 39% for POFA20 and 67% for POFA40. Since POFA20 meets the standards, it is however applicable in slab tracks.

1. Introduction
Demand for concrete sleepers is increasing with the increasing trend of demand for high-speed railway transportation. For 212 km long double-track high-speed railway projects, about 710,000 concrete sleepers are needed [1]. The world's railway lines are estimated to use around 2 billion sleepers, with a yearly demand of ten million new sleepers [2]. Meanwhile, by 2020, the production of cement is expected to reach 492,83 million tons, producing around 396,88 million tons of carbon emissions [3]. The cement content used in concrete sleepers ranges from 300 to 700 kg/m³ [4][5][6]. This higher cement consumption leads to environmental impacts since approximately 650 to 900 kg of CO₂ will be produced per one ton of cement which contributed to 7% of the total global CO₂ emissions [7][8][9]. This concern has allowed [4][5][6][10][11][12] to use alternative resource materials, for instance,
crumb rubber and mix plastic as a replacement aggregate. However, the replacement of cement or aggregate with crumb rubbers and plastic waste tends to reduce the strength of the concrete sleepers.

In Malaysia, up to 100 million tons of palm oil biomass was expected to increase in the year of 2020. Consequently, the environmental and health risks from the disposal of waste materials might also worsen [13][14]. As the waste materials have been dumped in the open air, it creates harmful environment [15][16]. The industry had faced the challenge from the 1990s where more than 1000 tons of POFA has been dumped into lagoons and landfills as shown in figure 1 [14].

[16] started studying the potential use of POFA as cementitious materials. However, they found that POFA has low pozzolanic properties, poor workability, and reduces the compressive strength of concrete. The low POFA pozzolanic reaction may be due to the high volume of unburned carbon due to the incompleteness of the burning process. Then, [17] grind the POFA to a finer particle at 10.1µm and use it as a cement replacement material in high strength concrete (HSC), the result shows that the compressive strength increased with an increasing percentage of POFA, producing HSC of strength around 79.8 to 85.9MPa, which was higher than control concrete. Comparing the raw POFA to treated POFA, raw POFA has lower silica dioxide, SiO\textsubscript{2} content, and higher loss on ignition, LOI than treated POFA. Besides, it also contains impurities such as fibers and coarse particles from incomplete combustion in the palm oil mill. Therefore, POFA is cannot be used directly in a raw form and required further treatment such as grinding and heating to enhance its pozzolanic properties [18][19][20][21][22].

![Figure 1. A disposal site for POFA at Muar palm oil mill.](image)

2. Materials
The materials that have been used were Ordinary Portland Cement (OPC), Palm Oil Fuel Ash (POFA), river sand, coarse aggregate, and tap water. POFA was used as a cement replacement material to improve the noise absorption in railway concrete sleepers.

2.1. Ordinary Portland Cement (OPC)
The OPC used for this study was CEM 1 type with a minimum strength class of 52.5 which in compliance with [23].

2.2. Palm Oil Fuel Ash (POFA)
POFA was collected from the palm oil mill located at Muar, Johore. The raw POFA was dried in the oven at 105 ± 5 °C for 24 ± 1 hr to remove the moisture content and reduce its carbon content. Figure 2 shows the POFA change its color from black to light grey after the heating process. The color change may happened due to the reduced carbon content during the burning process [19]. Next, POFA was sieved using a 0.30 mm (300µm) mesh according to [24] to remove the coarse particles that were incompletely combusted in the boiler.
2.3. Fine and coarse aggregates
The sand was used as a fine aggregate with a particle size of less than 5 mm. It was dried in the oven at 110 °C ± 5 for 24 hr to remove moisture content. Meanwhile, the coarse aggregate used was gravel with a size range from 5 mm to a maximum size of 20 mm. All aggregates used have complied with [25].

3. Methodology

3.1. The preparation of concrete sleeper
The general requirement of concrete sleepers was conformed to [26], where the minimum compressive strength was 55MPa at 28 days. The proportion of the control sample was derived based on the design of the experiment (DOE) method with a water-cement ratio (w/c) was 0.35. Three design mixes with 0%, 20%, and 40% of POFA content were tested and assigned as OPC, POFA20, and POFA40, respectively. A mixture with 0% of POFA was assigned as a control sample. Table 1 shows the details of the concrete mix design.

| Materials | POFA (%) | OPC (kg) | POFA (kg) | Aggregates Fine (kg) | Aggregates Coarse (kg) | Water (kg or liters) |
|-----------|----------|----------|-----------|----------------------|------------------------|----------------------|
| CONTROL   | 0        | 577.14   | 0         | 389.77               | 1285.33                | 195                  |
| POFA20    | 20       | 461.71   | 115.43    | 389.77               | 1285.33                | 195                  |
| POFA40    | 40       | 346.28   | 230.86    | 389.77               | 1285.33                | 195                  |

3.2. Water absorption test
The water absorption test indicates the porosity of the concrete. The test would be carried out following the [26] Part 1: Annex C: Method for measuring the water absorption of concrete sleepers at atmospheric pressure at the age of 7 and 28 days. The sequences of the test were as follows:

1) After removing the concrete from the water curing tank, it would be dried for 48 hours at 105 °C ± 2 °C in the oven and referred to as M1.
2) After drying, the samples were set up in a container partially filled with potable water at a temperature between 15 °C and 20 °C for a period of 24 hr.
3) After 24 hr, the water level has been increased to 5 mm above the top of the samples over a minimum of 15 min.
4) After 48 h, the samples were weighted in the water (hydrostatic weight) to obtain the mass M2. Figure 3 shows the hydrostatic weight test method.
5) The samples were wiped to eliminate any surface water and weighed to get the mass M3 (saturated weight).

The porosity of the sample has been calculated using equation (1). The requirement for porosity shall be less or equal to 12%.

Figure 2. The heated POFA had turned from (a) black to (b) light grey.
Where $V_p$ is the porosity, and $M$ is mass in kg.

$$V_p = \frac{M_2 - M_1}{M_3 - M_2} \times 100\%$$

(1)

3.3. Compressive strength test

The compressive strength test has been conducted at 7 days and 28 days of curing age with reference to [27] Part 3: Method for Compressive Strength. Three 100 mm$^3$ cube samples per mixture would be used in the test and the strength value would be the average of the samples. The concrete sample was cleaned from surface water before being placed on the compression machine as shown in figure 4. The loading rate was set at 0.6 ± 0.2 MPa/s (N/mm$^2$·s) and continuously increase at the rate of ± 10% until the sample fails.

4. Results and analysis

4.1. Water absorption test

The general requirement of the water absorption test was performed to determine the porosity of the concrete sleepers at a different percentage of POFA content. The test was conducted at 7 and 28 days of curing age. Figure 5 shows the result of the water absorption test at 7 and 28 days of curing age. From the result, we can observe that the water absorption was higher at an early age, and then reduced at 28 days of curing age. The water absorption was reduced by 14%, 22%, and 18% for OPC, POFA20, and POFA40, respectively. A similar result was obtained by [22] which recorded lower water absorption with longer curing age. A lower value of water absorption indicated that the concrete
sleepers have a lower porosity. This may due to the pozzolanic reactivity between the POFA and OPC which improves the microstructure of the structure and produced denser concrete [19][28][29][30].

![Figure 5. Water absorption (%) versus curing age (Day).](image1)

However, the results show that the water absorption of the concrete sleepers increases as the POFA replacement increased. As seen from figure 6, the water absorption of concrete sleepers increases as the POFA content increase at all curing age. On day 28 of curing age, the water absorption of the concrete sleepers was 6%, 7%, and 13% for OPC, POFA20, and POFA40, respectively. 20% of POFA increases water absorption by 14% compared to OPC. The highest water absorption recorded by the sample with 40% of POFA replacement, which increases the water absorption by 54% compared to the OPC sample. This shows that at a higher POFA replacement level, the permeability porosity of concrete sleepers was higher than the OPC. Similar results were observed from a study conducted by [20] where higher POFA content causes higher water absorption. This may due to ungrounded POFA which consists of larger and highly porous particles that tend to absorb more water [21][31]. Besides, larger particles of POFA produce a higher void in the concrete structure, thus resulted in higher permeable porosity.

According to [26], the porosity of the concrete sleepers should be lower than 12% in 28 days. However, POFA40 exceeds the maximum limit of 12%. Therefore it is inappropriate to be used in the railway operation. Hence, the optimum percentage of POFA replacement that fulfills the water absorption test was 20%.

![Figure 6. Water absorption (%) versus POFA replacement (%).](image2)
4.2. Compressive strength test

The compressive strength of concrete sleepers at 7 and 28 days of curing age is illustrated in figure 7. For the OPC sleepers, the compressive strength at day 7 and 28 of curing age was recorded as 44.04 MPa and 58.24 MPa, respectively. Since the compressive strength of OPC at 28 days was higher than 55 MPa, the design mix thus meets the [26] requirement and therefore, can be used as a reference sample of concrete sleepers. At an early age of 7 days, for concrete sleepers containing POFA replacement, all the compressive strength was lower than the OPC sample. This may due to the delayed formation of C-S-H gel due to high silica content over cement. A similar lower early strength trend recorded by [22,30–32]. At the early age of 7 days, the compressive strength was recorded at 31.11 MPa and 14.89 MPa for POFA20 and POFA40, respectively. However, at the later age of 28 days, the compressive strength of POFA20 and POFA40 increased to 35.52 MPa and 19.28 MPa, respectively. This shows that along with the curing age, a further pozzolanic reaction takes place between the silica in POFA and calcium hydroxide in cement to produce extra secondary calcium-silicate-hydrate (C-S-H), thus improved the microstructure of the concrete and therefore increase the compressive strength at a later age [19][21][33][34][35].

![Figure 7. Compressive strength (MPa) versus curing age (Day).](image)

Although the compressive strength of the concrete sleepers increases with the increased curing age, the compressive strength had reduced with a further increment of POFA replacement. Figure 8 shows the relationship between the compressive strength of the concrete sleepers and the POFA replacement content. From the results, the compressive strength was inversely proportional to POFA replacement content. As the percentage of POFA increase, the compressive strength reduced by 39% for POFA20 and 67% for POFA40. A similar trend was reported by [19] where the compressive strength of HSC decreases gradually as the POFA content increase. This may be due to the use of untreated POFA in this study that has low silica content due to its higher unburned carbon content and LOI value [20][29][36][37]. Thus, higher POFA content in POFA20 and POFA40 along with reduced cement content, resulting in the limitation of the reaction to cement and produce lower strength concrete than OPC [19][28]. Furthermore, a higher LOI value in POFA would cause excessive water absorption during the hydration process. As the result, the concrete sleepers with higher POFA content would losses their strength [19]. In terms of its physical properties, the POFA may have low pozzolanic properties due to its large particle size and porous structure [20][37][38][39]. However, although the compressive strength of POFA20 was 35.52 MPa and does not meet the minimum compressive strength of 55 MPa to be used as a concrete sleeper, it can be used in a slab track where the minimum compressive strength requirement was 27 MPa [4].
Compressive strength (MPa) versus the percentage of POFA replacement (%).

5. Conclusions

- The water absorption increases along with POFA content, indicating higher porosity. However, POFA40 recorded the highest water absorption with more than the allowable limit of 12%, therefore it is unsuitable to be used in the railway operation.
- The compressive strength of the concrete sleepers containing POFA increase with increasing curing age due to enhanced pozzolanic reaction which produced stronger concrete. However, POFA was not effective in improving the compressive strength of concrete sleepers. As 20% and 40% of POFA were utilized, the compressive strength of the concrete sleepers reduced below the minimum requirement of 55MPa, hence, they were not applicable as railway’s concrete sleepers. However, 20% of POFA can be used in slab tracks since the compressive strength exceeds 27 MPa.

6. References

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