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Feasibility study on the use of processed waste tea ash as cement replacement for sustainable concrete production

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ABSTRACT

In this study, processed waste tea ash (PWTA) generated by the boiler combustion of processed solid waste tea was used as a cement replacement at weights of 0%, 10%, 20%, 30%, and 40%. The effect of PWTA on the concrete properties was examined using the slump, density, compressive strength, porosity, chloride penetration depth, and microstructure as well as the embodied carbon content of concrete. Further, the contribution of the pozzolanic effect of PWTA to concrete strength was quantitatively analyzed using strength indices. The results showed that the slump and density of concrete decreased with the addition of PWTA. The concrete specimens with 10% PWTA achieved a similar compressive strength to that of control concrete at 28 days and a 4.57% higher value at 90 days due to the continuous pozzolanic reaction of PWTA. Strength indices also showed that the pozzolanic effect of 10% PWTA positively contributed to concrete strength at 90 days with a *P* value of 14.09%, which was higher than the percentage amount of PWTA used in the mixture. Owing to the pozzolanic reaction, the porosity and chloride penetration depth of 10% PWTA concrete at 90 days are lower by 4.2% and 9.4%, respectively, compared to those of control concrete. With the addition of PWTA up to 10%, the embodied carbon and carbon dioxide intensity could be reduced by 8.32% and 7.85%, respectively, compared with those of control concrete. These results suggest that PWTA is a useful replacement for up to 10% cement, enabling the production of innovative building materials for sustainable environment, with strengths similar to that of Portland cement.

1. Introduction

Nowadays, global warming, due to the increasing average atmospheric temperature, has become a serious problem. This has led to a severe climate change [1]. Carbon dioxide (CO_2) emissions are responsible for global warming and climate change due to the abundance of CO_2 and its ability to remain in the atmosphere for thousands of years [2]. Naturally, the urbanization process is one of the causes of increasing CO_2 emissions in the atmosphere. Massive movement of people to new places requires supporting infrastructure in the form of residential buildings, offices, and industries to support life activities. The building sector is placed as the main contributor to global greenhouse gas (GHG) emissions because it consumes a substantial portion of non-renewable energy and prompts the emission of a significant amount of CO_2 [3]. The CO_2 emission of the building sector accounts for approximately 39% of global CO_2

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emissions annually, owing to building operations (28%) as well as building materials and construction (11%) [4].

Construction of a buildings produces CO_2, either directly or indirectly. Approximately 14% of CO_2 is produced directly from burning of natural gas, diesel, light fuel oil, and other oil-based commodities, while indirect CO_2 generated from the use of electricity is approximately 85% [4]. From the building material perspective, concrete is the most carbon-emitting building material accounting for 60%–70% of the total embodied carbon [5,6]. The selection of appropriate sustainable building materials can reduce approximately 30% of embodied CO_2 emissions over the lifespan of a building [7]. Therefore, the use of low embodied carbon building materials is a significant challenge for the building sector to reduce the carbon footprint of buildings.

Concrete is a construction material widely used in infrastructure development, with its demand increasing year-on-year. This is attributed to the fact that concrete has outstanding performance, and its constituent materials are locally available. However, the concrete industry is accountable for approximately 10% of the global industrial CO_2 emissions [8,9]. The high CO_2 emission of concrete is due to the production of Portland cement and transportation of materials to the construction site. As the primary binding material in concrete, cement is a constituent that produces approximately 0.9 t of carbon dioxide for producing one ton of Portland cement [10,11]. Hence, alternative materials that can replace cement in concrete production and reduce the amount of embodied carbon in concrete are desired. Alternatively, US Portland Cement Association [12] recommended the use of supplementary cementitious materials (SCMs) as an effective way of lowering CO_2 emission from concrete production, which can readily be applied at cement and ready-mix plants at a low cost.

At the same time, a huge amount of solid waste materials generated from agricultural industry cause environmental burden and health issues due to insufficient waste management systems. Incorporating these waste materials in concrete is useful for reducing their negative impact on the environment. In the last few decades, agricultural waste ashes such as rice husk ash (RHA), sugarcane bagasse ash (SCBA), palm oil fuel ash (POFA), and wheat straw ash (WSA) have been incorporated as supplementary cementitious materials (SCMs) into concrete, and their effects on concrete properties have been well documented. For example, concrete containing 15% RHA showed an improvement in compressive strength by 25%, 33%, and 36% at 7, 28, and 56 days, respectively, compared to control concrete [13]. Additionally, a 10–25% improvement in modulus of elasticity was obtained with 10–30% RHA concrete [14,15]. Similarly, concrete containing 10% SCBA allows to obtain higher compressive strength than control concrete [16], and its modulus of elasticity is 13% greater than control concrete [17]. Furthermore [18], concluded that 10–20% replacement of cement with POFA is suitable to produce high strength and durable eco-friendly concrete. Additionally, the effect of WSA as cement replacement has been reported by Ref. [9]. The authors concluded that concrete containing 15% WSA showed remarkable improvement in strength, stiffness, toughness, and ductility at 90 days curing.

From the durability perspective, the porosity of concrete decreased by 13% and 12% when 7% and 15% ground RHA, respectively, were added to the mixture as cement replacement at 90 days [19]. In line with the porosity, chloride penetration depth of concrete containing 10–20% ground RHA was lower than that of control concrete [20,21]. The use of SCBA by 25% as cement replacement decreased the chloride penetration depth and among that replacement it increased [22]. Moreover, approximately 50% of the charge passed value reduced in concrete containing 20% SCBA [23]. In addition, partial cement replacement by 10–20% POFA enhanced the durability of concrete against chloride and sulfate attacks due to continuous pozzolanic reaction of POFA over the curing age [18]. Owing to their high silicate and aluminate contents, these agricultural waste ash act as pozzolanic materials that can produce secondary calcium silicate hydrate (C–S–H); thus, they help reduce the porosity and improve the mechanical and durability properties of concrete [24]. One of the agricultural industrial wastes whose amount continues to increase every year is processed waste tea ash (PWTA), which arises from the combustion of solid waste tea after processing as a boiler fuel. It is important to study the feasibility of PWTA as an alternative cement replacement, which is an uncommon SCM used in concrete, to produce low-embodied-carbon concrete materials.

Tea consumption has increased worldwide, with approximately five million tons of tea being consumed every year, and this figure is expected to increase [25,26]. China produces approximately 2.44-million-ton metrics of tea or 42% of the total global production [27]. In Indonesia, approximately 140,000 tons of tea were produced in 2019, generating a massive amount of solid waste tea after processing in the tea industry [28]. The majority of processed solid waste tea is burned at a temperature of 700 °C and used as boiler fuel to produce electricity for the extraction of tea in the plants. Further, approximately 8000 tons of processed waste tea ash are accumulated after boiler combustion [10].

PWTA is mostly disposed in open fields, which may lead to health-related issues and high environmental load. Recognizing this, PWTA can be potentially used as a locally available SCM for concrete to decrease the environmental load of this waste. An earlier study by Ref. [29] investigated the potential of used waste black tea ash by burning solid waste tea from domestic use in a controlled oven as a partial substitute of cement in mortar by 0, 2.5, 5, 7.5 and 10% weight and the effects of these combinations on the workability as well as compressive and flexural strength of mortar. From their study, it was found that the workability of mortar decreased as waste tea ash content increased. Moreover, approximately 10% improvement in compressive strength was observed in mortar containing 7.5% waste tea ash, while flexural strength was decreased as waste tea ash content increased. The authors suggested 7.5% waste tea ash as an optimum value for replacement of cement in mortar. Most recently [10], replaced 0, 10, 20, 30, 40 and 60% cement with waste tea ash in concrete paving block production. They observed that incorporating waste tea ash as cement replacement worsened the mechanical and durability properties of paving blocks. The authors argued that the coarse nature of waste tea ash particles used in their study (passing through 300 μm-size mesh) was the main cause of the mechanical strength and durability decrease of paving blocks.

Based on the literature review, a knowledge gap exists to explore the feasibility of PWTA as a cement replacement material, particularly for normal strength production; this application has not been thoroughly studied. Hence, the main objective of this study is to produce sustainable normal strength concrete by replacing cement with PWTA obtained from the boiler combustion of a processed solid waste tea in an Indonesian tea plant as a cement replacement in concrete. The PWTA was dried, ground, and sieved before use, and its effects on the properties and embodied carbon of concrete were evaluated. The current study is part of a broader research investigating the potential use of locally available waste material as an alternative binder in the production of innovative building materials for a sustainable environment.

2. Experimental procedures

2.1. Materials

Portland cement type I conforming to SNI 15 2049-2004 [30] was used in this study. Natural river sand was used as a fine aggregate with a specific gravity of 2.46 and a fineness modulus of 2.61. Crushed stone with a maximum size of 19 mm and specific gravity of 2.78 was used as the coarse aggregate. Potable water was used for the mixing and curing of concrete.

The PWTA was collected from a local tea industry in Gowa, Indonesia. The PWTA was first dried in an oven (105 °C) for 24 h and then cooled at ambient temperature. After the cooling process, it was sieved through a 300 µm mesh to remove coarse particles and then ground using a Los Angeles abrasion machine until 5% was retained in a 75 µm mesh. The PWTA was collected and used as a partial replacement for the cement. The suitability of biomass ash passed through a 75 µm sieve as cement replacement in the concrete has been reported by Refs. [31,32]. A similar method was adopted to prepare the PWTA in this study.

Table 1 presents the physical and chemical compounds of cement and PWTA after grinding. The PWTA exhibited lower specific gravity than cement (i.e., 2.18 and 3.06). The particle size distribution of PWTA was in the range between 8.49 and 49.26 µm, while that of cement was between 2.10 and 34.64 µm. This indicates that PWTA comprises larger particle sizes than cement, as shown in Fig. 1. PWTA contains a high amount of SiO_2 (55.76%), followed by CaO (22.32%), which acts as lime [33]. Other oxides, including Al_2O_3, Fe_2O_3, and K_2O, were also present in small quantities. The SO_3 and LOI values of the PWTA were 0.32% and 6.14%, respectively. Therefore, PWTA can be classified as a Class C pozzolan according to ASTM C 618 [34]. Fig. 2 shows the SEM images of the PWTA after grinding, which shows that PWTA comprises irregularly shaped particles with porous texture surfaces.

2.2. Concrete mix design and specimen preparation

All the concrete specimens were designed with a constant water-to-binder (w/b) ratio of 0.513. Five mix proportions were prepared by replacing cement with 0%, 10%, 20%, 30%, and 40% of PWTA by weight, as listed in Table 2. Concrete was produced using a rotary drum mixer capacity of 150 L. First, cement/PWTA and fine and coarse aggregates were dry-mixed for 30 s; then, water was added to the mixtures, and all the concrete components were mixed for 2 min. The mixture was then stirred manually for 90 s to mix the material adhering to the bottom of the mixer. Subsequently, mixing was continued for 1 min to obtain a homogeneous fresh concrete mixture. Thereafter, the fresh concrete mixtures were cast into cube and cylindrical steel molds, demolded after 24 h, and then cured in tap water until testing.

2.3. Testing methods

The slump and fresh density of concrete were measured in accordance with ASTM C143 [35] and ASTM C138 [36], respectively, to investigate the effect of PWTA on the fresh properties of concrete.

The hardened properties of concrete were tested based on the compressive strength, modulus of elasticity, porosity, and chloride penetration depth. The compressive strength of the concrete was measured in 150 mm × 150 mm × 150 mm cube specimens at 7, 28, and 90 days of water curing in accordance with BS EN 12390-3 [37]. The modulus of elasticity of the concrete specimens was tested after 28 days of water curing on cylindrical specimens of 100 mm in diameter and 200 mm in height, as per ASTM C469 [38].

The porosity test was conducted on cube specimens with dimensions of 100 mm × 100 mm × 100 mm at 28 and 90 days of water curing. The cube specimens were removed from the water tank, and the weight was measured immediately to obtain the weight of the sample in water (W_w). Subsequently, the surface of the cube specimens was wiped off with a clean towel and re-weighed for the

Table 1
Physical and chemical compounds in cement and PWTA.

Properties	Cement	PWTA
Physical properties:		
Specific gravity	3.06	2.18
D_{10} (µm)	2.10	8.49
D_{50} (µm)	13.27	25.14
D_{90} (µm)	34.64	49.26
Retained in the mesh #200 (%)	–	5
Chemical compound (%):		
Silicon dioxide (SiO_2)	19.03	55.76
Aluminum trioxide (Al_2O_3)	5.29	3.41
Iron oxide (Fe_2O_3)	3.42	1.83
Calcium oxide (CaO)	62.27	22.32
Sulfur trioxide (SO_3)	1.62	0.32
Magnesium oxide (MgO)	1.13	0.11
Potassium oxide (K_2O)	0.47	4.13
Loss of ignition (LOI)	3.03	6.14
Others	3.74	6.25

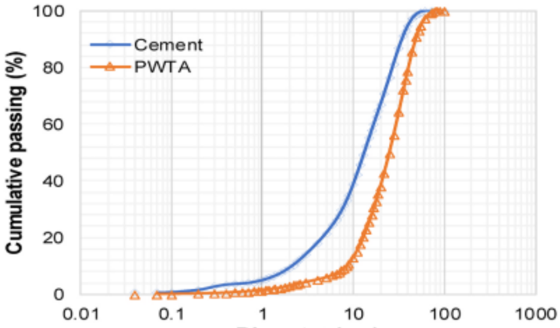

Fig. 1. Particle size distributions of cement and PWTA.

saturated surface dry weight (W_{ssd}). Subsequently, the specimens were dried in an oven at 105 °C until they reached a constant weight (W_{od}). The porosity (ρ) of the concrete specimens was determined using Eq. (1):

$$\rho = \frac{(W_{ssd} - W_{od})}{(W_{ssd} - W_{w})}\ x\ 100\%. \tag{1}$$

Many researchers have used this method to calculate the porosity of cement-based materials [9,20,39].

A chloride penetration depth test was conducted on cylindrical specimens with dimensions of 100 mm × 100 mm, obtained by cutting half of the cylinder's concrete specimens with dimensions of 100 mm × 200 mm at the age of 90 days. All the sides of the specimen were covered with epoxy, except for the top surface of the specimen, to ensure that chloride penetration occurred only in one direction. The specimens were then immersed in a 5% NaCl solution for 28 and 90 days (Fig. 3a) to simulate the aggressive condition of concrete members in the marine environment [40]. The chloride penetration depth was determined by spraying the split surface of the concrete with 0.1 N silver nitrate ($AgNO_3$) solution as suggested by Ref. [41]; and the bright color on the concrete specimens indicated the chloride penetration depth (Fig. 3b). The chloride penetration depth was measured at an interval of 10 mm along the width of the sample and at least 10 mm from the side edges, as illustrated in Fig. 3b. The measured values with coefficients of variation greater than 15% were removed. The final chloride penetration depth is the average of all the measurements. For all the hardened tests, the average results of the three specimens for each mixture are reported.

In addition, scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS) were conducted on a selected concrete mixture to determine the effect of PWTA on the microstructure of concrete. A small fragment from the concrete specimen after the compressive strength test at 90 days was used for the SEM and EDS analyses.

2.4. Embodied carbon assessment

The embodied carbon of each mixture containing PWTA was estimated based on the volume of the concrete. The CO_2 emissions of the concrete components (water, cement, fine and coarse aggregates, and PWTA) were obtained from the literature [10,42], as listed in Table 3. The embodied carbon of concrete was estimated using Eq. (2):

$$CO_{2e} = \sum_{i=1}^{n} (W_i\ \ x\ \ CO_{2i}), \tag{2}$$

where CO_{2eq} is the embodied carbon of concrete (kg-CO_2/m^3), W_i is the weight per unit volume of concrete component (kg/m^3), and CO_{2i} is the carbon dioxide emission for each concrete component (kg-CO_2/kg).

3. Results and discussion

3.1. Slump and fresh density

Table 4 presents the effects of the PWTA content on the slump value and fresh density of the concrete mixtures. The slump value decreased with increasing PWTA content. The slump values of concrete containing 10%, 20%, 30%, and 40% PWTA as cement replacement were 17%, 32%, 102%, and 286% lower than that of the control concrete, respectively. This can be attributed to the porous structure and irregular shape of the PWTA absorbing some water for workability, resulting in a more pronounced reduction in the slump value at higher replacement levels of the PWTA. These results are in agreement with those obtained by Refs. [10,29]; who found that the addition of waste tea ash increased the water demand of fresh mortar and concrete. Nevertheless, all the mixtures containing PWTA showed slump values above 20 mm, which is still suitable for practical applications.

Similarly, as listed in Table 4, the fresh density decreases with increasing PWTA content. For example, the fresh density of the control concrete was 2446.8 kg/m^3, corresponding to reductions of 1.35, 2.73, 6.27, and 8.86% for 10%, 20%, 30%, and 40% PWTA, respectively. This reduction in the fresh density may be attributed to the lower specific gravity of PWTA compared to that of cement (i.e., 2.18 and 3.05 for PWTA and cement, respectively). This observation is similar to that made by Ref. [10]; who found that the density

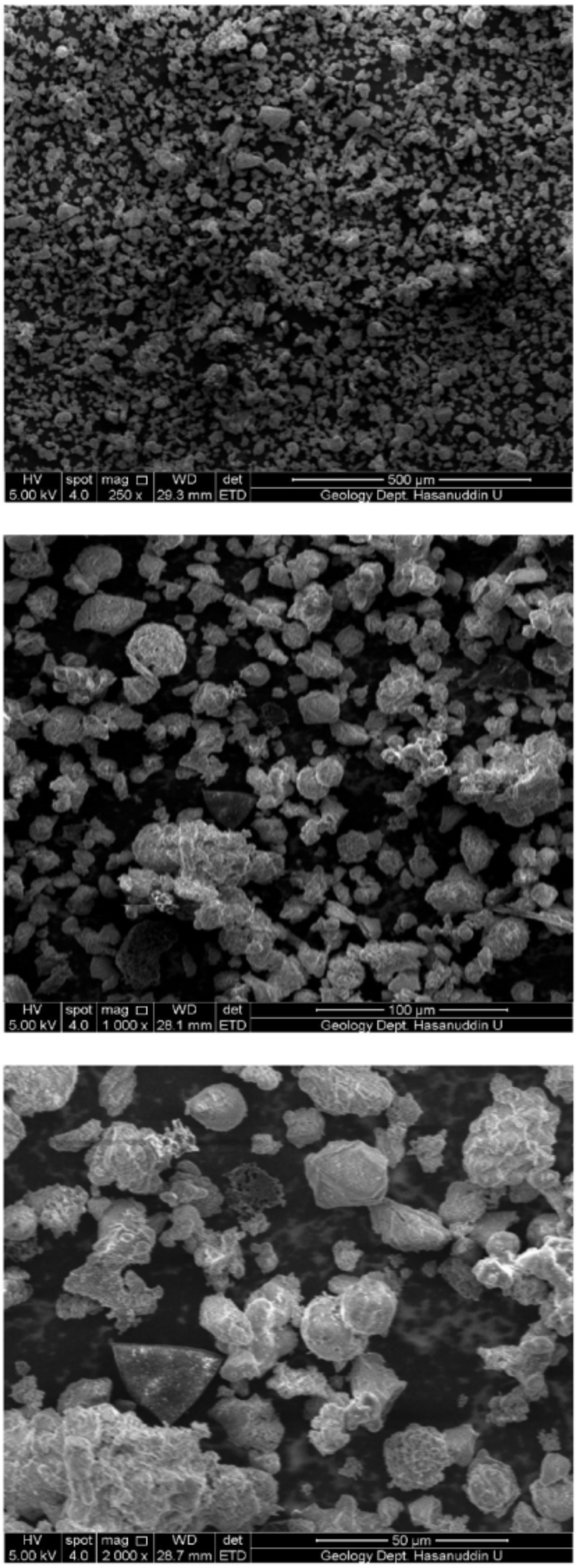

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Fig. 2. SEM image of a PWTA particle at magnitudes of (a) 250x, (b) 1000x, and (c) 2000x

Table 2
Mix proportion of concrete used.

Mix ID	Water (kg/m^3)	Cement (kg/m^3)	PWTA (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	w/b
C	189	367	0	731	1096	0.513
10%PWTA	189	331	37	731	1096	0.513
20%PWTA	189	294	73	731	1096	0.513
30%PWTA	189	257	110	731	1096	0.513
40%PWTA	189	220	147	731	1096	0.513

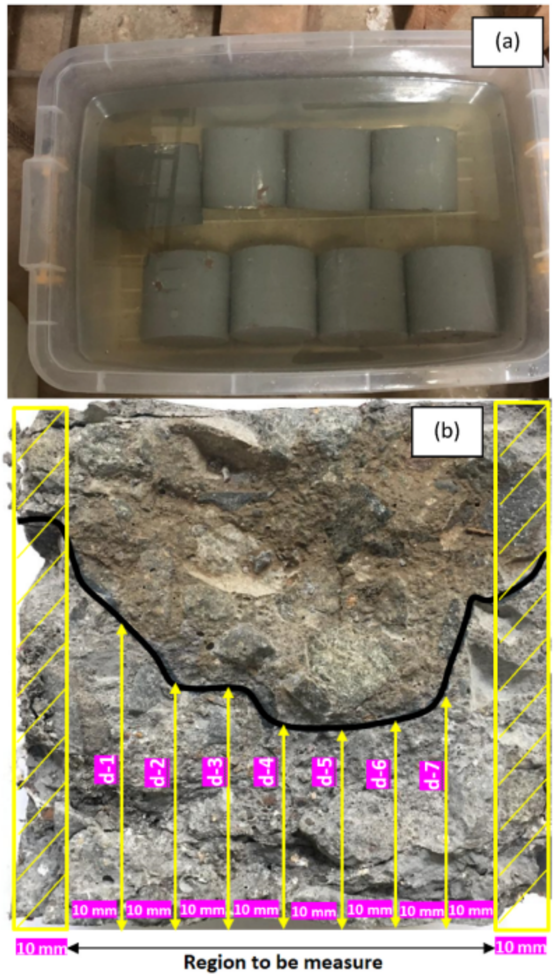

Fig. 3. Chloride penetration depth test: (a) specimens immersed in a 5% NaCl solution and (b) concrete after spraying 0.1 N $AgNO_3$ solution.

Table 3
CO_2 emission of concrete components.

Concrete components	Water	Cement	PWTA	Fine Aggregate	Coarse Aggregate
CO_2 emission, kg-CO_2/kg	0.000196	0.931	0.01293	0.0026	0.0075

Table 4
Slump and fresh density of concrete mixtures.

Mix ID	Slump (mm)	Fresh density (kg/m^3)
C	70	2446.8
10%PWTA	60	2413.8
20%PWTA	45	2380.1
30%PWTA	30	2293.4
40%PWTA	22	2230.1

of concrete blocks decreases with increasing PWTA content. Several studies have also reported that replacing cement with agricultural wastes, such as rice husk ash, sugarcane bagasse ash, and palm oil fuel ash, results in a lower density than that of the control concrete [17,43,44].

3.2. Compressive strength

Fig. 4 shows the compressive strengths of the concrete mixtures at 7, 28, and 90 days. The compressive strength increased with the curing age. At early ages (7 days), the compressive strength of the control concrete exceeded that of the concrete with the PWTA. The control concrete achieved a compressive strength of 19.75 MPa, which was 20.58, 21.69, 38.63, and 56.12% higher than those achieved by 10%PWTA, 20%PWTA 30%PWTA, and 40%PWTA, respectively. This is owing to the delayed hydration process of the concrete containing PWTA at an early age, which has also been reported in previous research on concrete with pozzolanic materials [45].

At 28 days, the compressive strength of 10%PWTA and 20%PWTA increased significantly to a value closer to that of the control concrete, with compressive strength values of 25.15, 25.02, and 25.66 MPa for the control, 10%PWTA, and 20%PWTA concrete, respectively. The compressive strength of 10%PWTA and 20%PWTA satisfied the SNI 2847-2019 [46] for the minimum compressive strength for concrete structural applications (i.e., 21 MPa). These improvements in the compressive strength could be attributed to the filler effect and pozzolanic reaction of PWTA after 28 days of curing. On the other hand, the 30%PWTA and 40%PWTA specimens had lower compressive strength values of 25.66% and 42.91%, respectively, than the control concrete. The reduction in the compressive strength is due to the low cement content in the 30%PWTA and 40%PWTA mixtures. A similar reduction in the compressive strength at a higher cement replacement level with the biomass ash has been reported in previous studies [47,48]. Another possible reason for the reduction in the compressive strength was the increase in the air void of the concrete because of the lack of plasticity of the fresh mixture at a higher replacement level of the PWTA [10,29].

At a longer curing period (90 days), 10%PWTA reached the highest compressive strength of approximately 33 MPa, which was 4.57, 8.08, 28.17, and 44.76% higher than those of the control concrete, 20%PWTA, 30%PWTA, and 40%PWTA, respectively. The highest compressive strength obtained for 10%PWTA at 90 days indicates that the continuous pozzolanic reaction in the PWTA concrete produced a strong calcium silicate hydrate (C–S–H) that improved the compressive strength at a later age. The improvement in the compressive strength at longer curing periods (90 days) of concrete or mortar with the pozzolanic material has also been reported in recent studies [9,45]. [45] reported that concrete with a 15% shell sunflower ash showed a 27.30% higher compressive strength than normal concrete at 90 days. Similarly [9], found that incorporating 10% wheat straw ash resulted in a 12.59% higher compressive strength than that of normal concrete at 90 days. The addition of pozzolanic materials into concrete could act as a filler, filling the capillary pores in concrete and creating denser microstructures, resulting in a higher compressive strength at later ages. Based on the compressive strength results obtained in this investigation, 10%–20% PWTA is recommended as a cement replacement for concrete.

3.3. Modulus of elasticity

The modulus of elasticity was calculated from the stress–strain relationship of the concrete specimens at 28 days (Fig. 5). Fig. 6 shows the modulus of elasticity of each concrete mixture. No change was observed in the modulus of elasticity for up to 20%

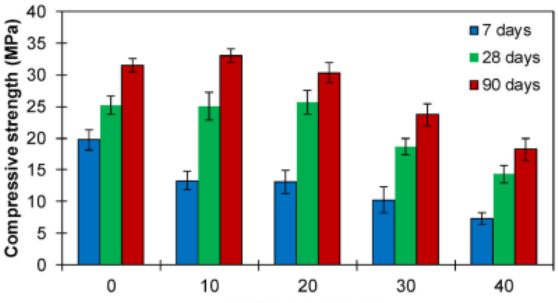

Fig. 4. Compressive strength of concrete mixture at different curing ages.

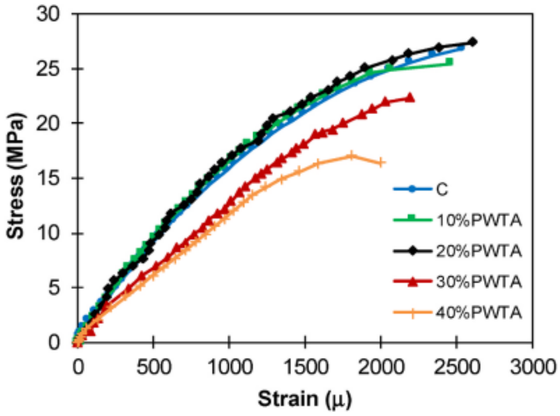

Fig. 5. Stress–strain curve of concrete with different PWTA contents at 28 days.

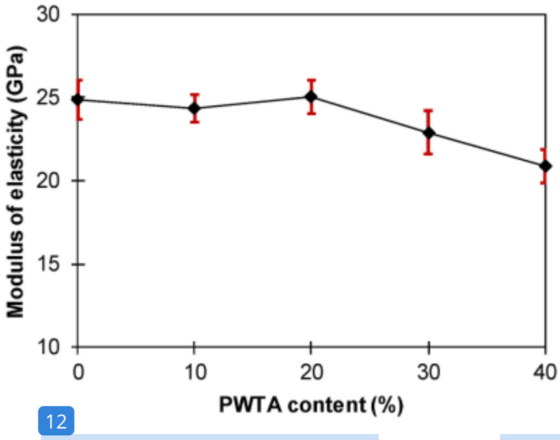

Fig. 6. Modulus of elasticity of concrete with different PWTA contents at 28 days.

replacement of cement with the PWTA; beyond that value, the modulus of the elasticity of the PWTA concrete decreased with increasing PWTA content in the mixture. This indicates that the compressive strength influences the modulus elasticity of the PWTA concrete. The higher the compressive strength is, the higher the modulus elasticity becomes. Similar results have been reported by Refs. [43,49] for concrete containing palm oil fuel ash as cement replacement, where the modulus of elasticity of concrete was found to

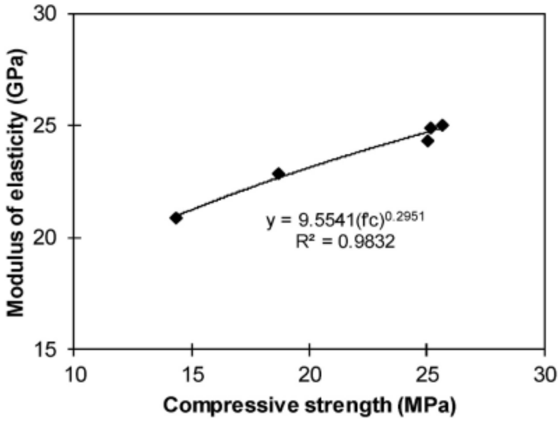

Fig. 7. Linear relationship between modulus of elasticity and compressive strength of concrete.

depend on the compressive strength value. Fig. 7 shows the relationship between the compressive strength and modulus of elasticity of concrete at 28 days. A strong correlation was found between these two properties, indicating that the modulus of elasticity is associated with the compressive strength of concrete containing PWTA.

Furthermore, the peak strains of 10%PWTA and 20%PWTA were close to those of the control concrete, which indicates a similar ductility behavior, while 30%PWTA and 40%PWTA exhibited lower strain values of approximately 30% and 32%, respectively, compared with the control concrete. This indicates that the drawbacks of the interfacial transition zone of concrete at a higher replacement level of PWTA are caused by the increased air void of concrete owing to the lack of plasticity of fresh concrete.

3.4. Indices of pozzolanic effect of PWTA

In order to quantify the pozzolanic effect of PWTA as a cement replacement in concrete, an analysis using strength indices was carried out as per previous studies by Refs. [50,51]. Here, the specific strength ratio is expressed as

$$R = f/q \tag{3}$$

where f is concrete compressive strength (MPa), q is the cement or PWTA percentage of the cementitious materials, R is the ratio of contributions to strength from unit cement and PWTA, R_c represents the contribution of unit cement to strength without PWTA, R_m expresses the contribution of unit PWTA to strength, and R_p is the contribution of pozzolanic effect to strength owing to PWTA, defined as

$$R_p = R_m - R_c \tag{4}$$

K is the specific strength ratio, expressed as

$$K = R_m / R_c \tag{5}$$

Additionally, the percentage value of the contribution of pozzolanic effect to strength (P) can be determined by the formula

$$P = (\mathrm{R_p} / \mathrm{R_m}) \times 100\% \tag{6}$$

If the P value is higher than the amount of PWTA added to the mixture, there is positive contribution of pozzolanic effect of PWTA to concrete strength. Steps to follow to calculate the P value for 10%PWTA specimens at 28 days have been listed below.

- Calculate the strength specific ratio for Control (R_c) and 10%PWTA specimens (R_m) at 28 days using Eq. (1).

$$R_c = \mathrm{f_{\_Control}} / \mathrm{q_{\_Control}} = 25.15/100 = 0.2515$$

$$R_m = \mathrm{f_{\_10\%PWTA}} / \mathrm{q_{\_10\%PWTA}} = 25.02/90 = 0.278$$

- Define the contribution of pozzolanic effect to the strength (R_p) and specific strength ratio (K) of the 10%PWTA specimens using Eqs. (2) and (3).

$$R_p = R_m - R_c = 0.278–0.2515 = 0.0265$$

$$K = R_m / R_c = 0.278/0.2515 = 1.105$$

- Then, determine the percentage value of the contribution of the pozzolanic effect to the strength of 10%PWTA (P) using Eq. (4).

$$P = (R_p / R_m) \text{ x } 100\% = (0.0265 / 0.278) \text{ x } 100 = 9.53\%$$

Table 5 presents the effect of PWTA as a cement replacement on strength index parameters (R_m, R_p, K, and P) of all concrete specimens at 28 and 90 days. From Table 5, it is evident that 10%PWTA causes an increase in P value with curing age by 9.53–14.09% from 28 to 90 days, respectively; this P value is higher than the amount of PWTA added to the concrete mixture, indicating the positive pozzolanic effect of 10%PWTA on concrete strength. Beyond 10% replacement of PWTA, the P value is less than the amount of PWTA added to the concrete mixture, indicating smaller pozzolanic contribution to concrete strength. These results align with the compressive strength test results, where 10%PWTA achieved higher compressive strength than control concrete at 90 days owing to the continuous pozzolanic reaction in the PWTA concrete.

Table 5
Strength index parameters of concrete.

Mix ID	q (%)	f (MPa)		R_m		R_p		K		P (%)	
		28 d	90 d	28 d	90 d	28 d	90 d	28 d	90 d	28 d	90 d
C	100	25.15	31.5	0.25	0.32	0	0	1	1	0	0
10%PWTA	90	25.02	33	0.28	0.37	0.03	0.05	1.11	1.16	9.53	14.09
20%PWTA	80	25.66	30.34	0.32	0.38	0.07	0.06	1.28	1.2	21.59	16.94
30%PWTA	70	18.69	23.7	0.27	0.34	0.02	0.02	1.06	1.07	5.81	6.96
40%PWTA	60	14.36	18.23	0.24	0.3	−0.01	−0.01	0.95	0.96	−5.08	−3.68

3.5. Porosity

Porosity is an important indicator that affects the durability of concrete, and the ability of aggressive ions to penetrate depends on porosity. Fig. 8 presents the porosities of concrete at 28 and 90 days. The porosity of concrete tended to increase with the addition of PWTA at 28 days. The control concrete showed a porosity value of 9.15%, which was 3.28, 7.54, 15.31, and 20.66% lower than those of 10%PWTA, 20%PWTA, 30%PWTA, and 40%PWTA, respectively. However, as the curing age was increased to 90 days, the 10%PWTA concrete showed a lower porosity value of approximately 4.2% compared with that of the control concrete, while the porosity of 20% PWTA was close to that of the control concrete. This reduction in the porosity might be due to the pozzolanic activity of PWTA, which reacts with calcium hydroxide ($Ca(OH)_2$) generated from cement hydration to produce secondary C–S–H that fills the capillary pores of the concrete, leading to a reduction in porosity. Beyond 20% replacement of PWTA, the porosity of concrete exceeds that of the control concrete. This might be due to the reduced amount of cement at higher replacements of PWTA, which delays the pozzolanic reaction in producing secondary C–S–H. Furthermore, the texture surface of PWTA as shown by SEM images is porous in nature, which may increase the porosity of concrete. This is supported by the results of the indices of pozzolanic contribution of PWTA, according to which 10% PWTA showed a positive contribution to concrete strength with increased curing age owing to the continuous pozzolanic reaction of PWTA. In contrast, at a higher replacement level, it failed to contribute to the concrete strength. In addition [52], reported that concrete containing 20% POFA showed 12.5% and 18.2% reduction at 28- and 90-days curing, respectively. Fig. 9 shows the correlation between the porosity and compressive strength of concrete. A good correlation was found between the porosity and compressive strength; the lower the compressive strength of concrete is, the higher the porosity is.

3.6. Chloride penetration

Fig. 10 shows the chloride penetration depth of concrete after immersion in a 5% NaCl solution for 28 and 90 days. The chloride penetration depth increased with the exposure time. Cement replacement with 10% PWTA showed better resistance against chloride ingress than the control, 20%PWTA, 30%PWTA, and 40%PWTA at 28 and 90 days. For instance, the chloride penetration depth of 10% PWTA was approximately 17.75 mm at 28 days of exposure, which was 13.52%, 18.70%, 27.63%, and 34.26% lower than those of the control, 20%PWTA, 30%PWTA, and 40%PWTA, respectively. At 90 days of exposure, a penetration depth of 37.57 mm was observed for 10%PWTA, whereas it was 41.47, 42.91, 53.65, and 55.16 mm for the control, 20%PWTA, 30%PWTA, and 40%PWTA, respectively. The results revealed that inclusion of 10% PWTA in the concrete mixture resulted in denser concrete owing to pozzolanic activity, which produced C–S–H solidification, reduced the void size, and made denser concrete with a lower porosity and chloride penetration depth [40]. The chloride penetration depth is in line with the results of the porosity test of the specimens at 90 days for concrete containing PWTA.

3.7. SEM and EDS

Fig. 11 shows the SEM images of the control, 10%PWTA, and 30%PWTA specimens cured for 90 days in tap water. The microstructures of the concrete significantly affect its mechanical and durability performance. As shown in Fig. 11a, the concrete control surface contains a significant amount of CH, pores, and microcracks. A high amount of cement in the control specimens leads to an increase in the hydration temperature of concrete, increasing the risk of internal cracking. Furthermore, the discontinuation of the C–S–H particle distribution in the control specimens might have reduced the concrete strength. In contrast, the inclusion of PWTA with 10% cement yielded a denser and more compact microstructure compared with the control concrete (Fig. 11b). The SEM images confirmed that fewer voids and homogenous microstructures with less CH were observed in 10%PWTA concrete. This is attributable to the continuous production of additional C–S–H gel from the reaction between $Ca(OH)_2$ of cement hydration and PWTA that fills up the voids in concrete, producing higher compressive strength, lower porosity, and chloride penetration depth than the other mixtures at 90 days. At a higher replacement level (i.e., 30%PWTA), more significant amounts of CH and pores with less compact microstructures were observed, leading to a reduction in concrete performance (Fig. 11c).

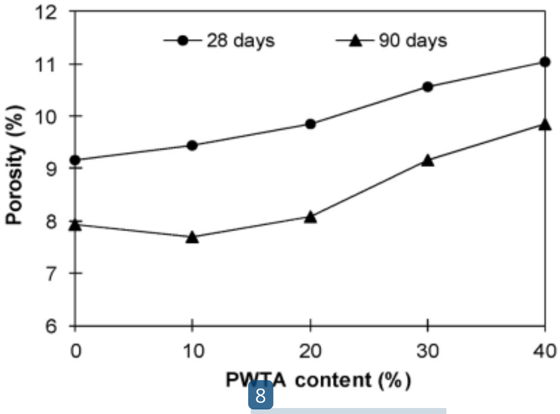

Fig. 8. Porosity of concrete at 28 and 90 days.

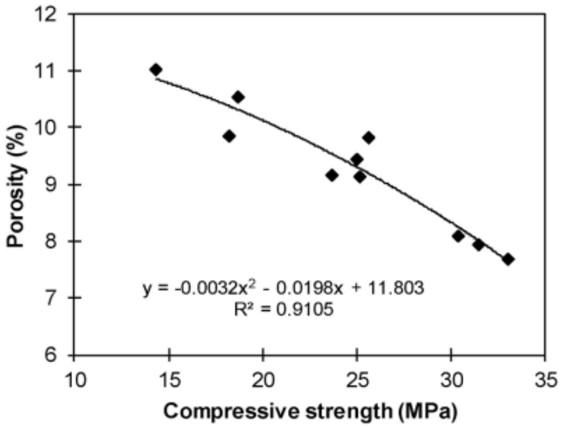

Fig. 9. Relationship between porosity and compressive strength.

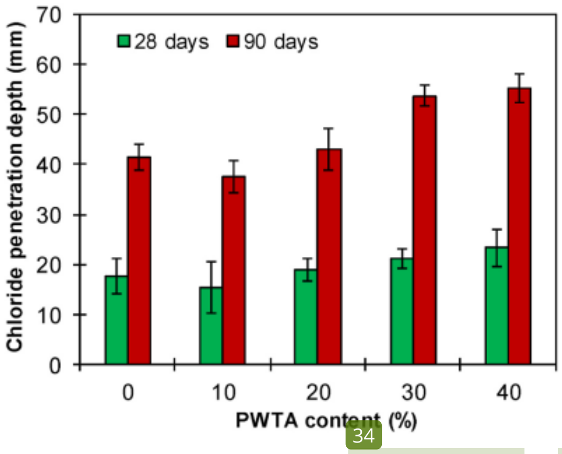

Fig. 10. Chloride penetration depth of concrete after 28 and 90 days of immersion in 5% NaCl solution.

Fig. 12 presents the trace elements of the control, 10%PWTA, and 30%PWTA concrete using EDS. Primary trace elements, such as Ca, Si, Fe, and Al, were detected, similar to the chemical compositions of cement and PWTA. As shown in Fig. 12a, there is no significant consumption of Ca during the hydration process. However, this type of unreacted Ca produces a strong C–S–H gel when reacted with an appropriate amount of pozzolanic materials containing a high silicate content [45]. As shown in Fig. 12b, high Si and low Ca intensities can be observed in the 10% PWTA specimen, indicating that PWTA pozzolans and calcium hydroxide from cement hydration that produced a secondary CSH gel eventually resulted in a denser microstructure. On the other hand, the 30% PWTA specimens showed that the Si and Ca intensities remained high, as shown in Fig. 12c. This might be owing to the slow hydration reaction that occurred, which inhibited the increase in the compressive strength. Furthermore, the Ca/Si ratio plays a vital role in the strength characteristics of concrete [53,54]. EDS analysis showed that the Ca/Si ratio of 10%PWTA concrete was lower than those of the control and 30%PWTA concrete after 90 days. The low Ca/Si ratio is indicated by the high number of Si–O bonds rather than the Ca–O bonds, which is in line with the EDS analysis. The EDS analysis results matched well with the strength, porosity, chloride penetration depth, and SEM images.

3.8. Embodied carbon assessment

Incorporating PWTA as a cement replacement in concrete could improve the strength, durability, and microstructures of concrete and reduce the embodied carbon in concrete. Table 6 presents the estimation of $CO_{2\text{-eq}}$ in each concrete mixture. Evidently, $CO_{2\text{-eq}}$ of concrete decreased with increasing PWTA content. The control concrete generated $CO_{2\text{-eq}}$ of approximately 358.71 kg/m^3 and it reduced by 8.32, 16.65, 24.94, and 33.29% when 10%, 20%, 30%, and 40% of PWTA was used as the cement replacement, respectively.

The $CO_{2\text{-eq}}$ intensity value was estimated based on the method proposed by Ref. [55] by dividing $CO_{2\text{-eq}}$ of concrete with the compressive strength of concrete at 28 days. Fig. 13 presents the $CO_{2\text{-eq}}$ intensity values for all the concrete mixtures. The 10%PWTA and 20%PWTA concrete specimens showed $CO_{2\text{-eq}}$ intensity values of 13.15 and 11.65 $kg{\cdot}CO_{2\text{-eq}}.m^{-3}$/MPa, which were lower by

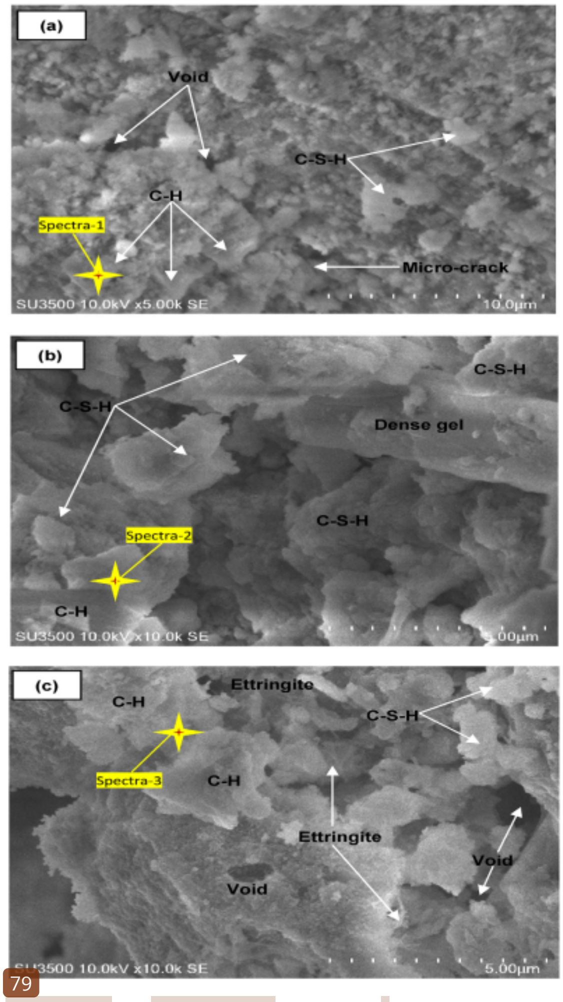

Fig. 11. SEM images of the (a) control, (b) 10%PWTA, and (c) 30%PWTA concrete at 90 days.

approximately 7.85% and 18.32%, respectively, than that of the control concrete that exhibited a similar compressive strength at 28 days. Beyond 20% replacement with the PWTA, the $CO_{2\text{-eq}}$ intensity value exceeded that of the control concrete, which can be attributed to the lower compressive strength of PWTA concrete at 28 days. These results demonstrate that replacing cement with 10%–20% PWTA can help produce eco-friendly concrete with lower embodied carbon and avoid landfilling associated with the disposal of this waste material. Further, the utilization of 10%–20% of PWTA as cement replacement in concrete can be a benchmark for future research on PWTA concrete.

4. Conclusions

In this study, the feasibility of PWTA as a cement replacement in concrete was investigated, and its effects on the embodied carbon in concrete were discussed. The following conclusions can be drawn from the test results:

1. The slump value of concrete decreased with an increase in the amount of PWTA in the mixture but was still above 20 mm for practical application.
2. PWTA concrete exhibited a lower fresh density than normal concrete. This is because the specific gravity value of PWTA is lower than that of cement, resulting in a decrease in the fresh density of concrete with PWTA.
3. The concrete specimen with up to 20% PWTA replacement did not exhibit any adverse changes in its compressive strength at 28 days. Furthermore, the 10%PWTA concrete exhibited 4.57% higher compressive strength at 90 days compared to control concrete. This is because of the continuous pozzolanic reaction of PWTA and cement in producing secondary C–S–H gel, which caused the microstructures of concrete to become dense.

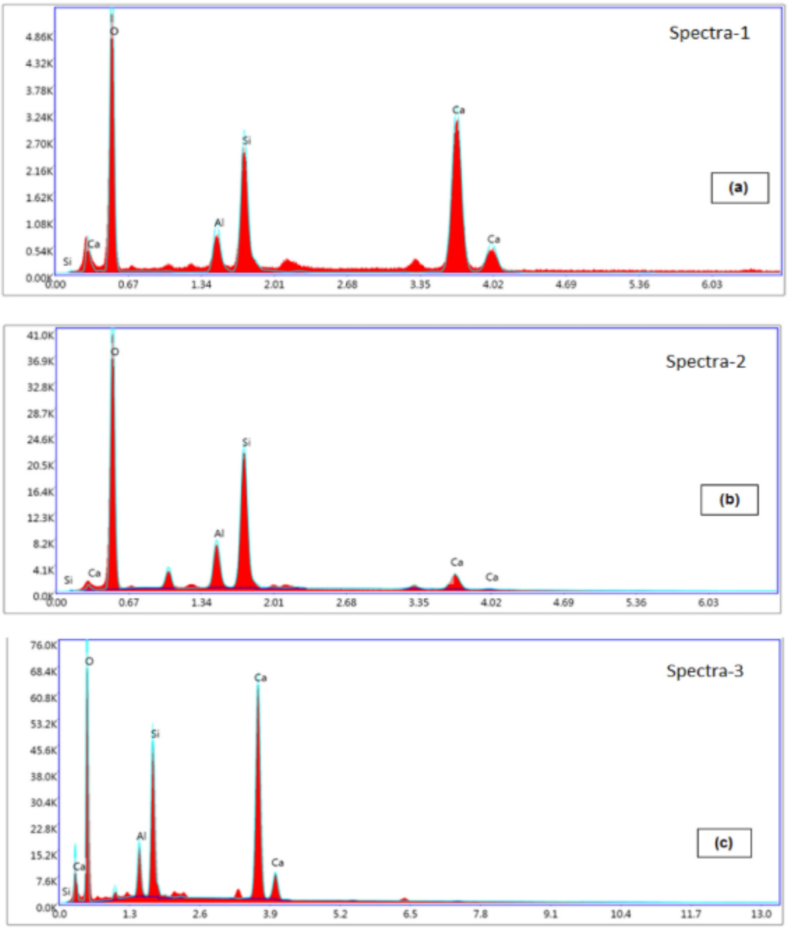

Fig. 12. EDS spectra of the (a) control, (b) 10%PWTA, and (c) 30%PWTA concrete at 90 days.

Table 6
Estimation of $CO_{2\text{-eq}}$ of each concrete mixture.

Concrete components	Mix ID				
	C	10%PWTA	20%PWTA	30%PWTA	40%PWTA
Water (kg/m^3)	0.037	0.037	0.037	0.037	0.037
Cement (kg/m^3)	303.4	273.06	242.72	212.38	182.04
PWTA (kg/m^3)	0	0.47	0.96	1.44	1.91
Fine aggregate (kg/m^3)	10.23	10.23	10.23	10.23	10.23
Coarse aggregate (kg/m^3)	45.04	45.04	45.04	45.04	45.04
Total $CO_{2\text{-eq}}$ (kg/m^3)	358.71	328.85	298.99	269.13	239.27

4. The pozzolanic effect of 10%PWTA positively contributed to concrete strength as *P* value increased with curing age, higher than the percentage unit of PWTA added to the mixture.
5. No change was observed in the concrete modulus of elasticity up to 20% PWTA, with the peak strain close to that of control concrete, indicating similar ductility.
6. Owing to the pozzolanic reaction of PWTA, the porosity of concrete containing 10% PWTA was lower than that of the control concrete, particularly at later ages (90 days).
7. The replacement of cement with 10% PWTA enhances the resistance of concrete against chloride penetration owing to the pore-filling effects of the pozzolanic reaction of PWTA, leading to a reduction in the number of concrete voids, thus blocking the movement of chloride ions into concrete.

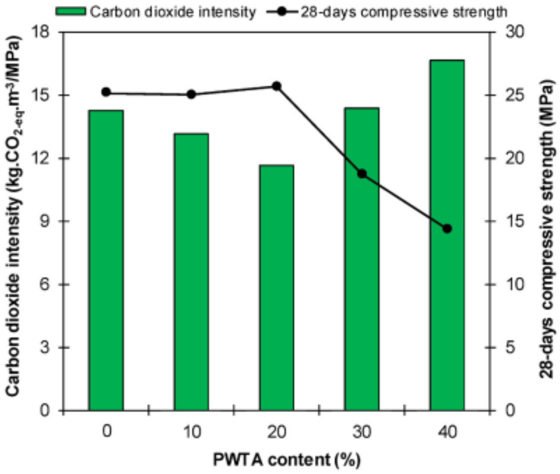

Fig. 13. CO$_{2\text{-eq}}$ intensity value of each mixture.

8. SEM observations indicated that 10%PWTA concrete exhibited fewer voids and a more homogenous microstructure than the control concrete owing to the continuous production of additional C–S–H in PWTA concrete. This is in line with the EDS analysis, where 10%PWTA concrete showed a high Si intensity and low Ca/Si ratio compared with the control concrete.
9. The replacement of cement with PWTA up to 20% reduced the embodied carbon and CO$_{2\text{-eq}}$ intensity values by 16.65% and 18.32%, respectively, compared with the control concrete. This confirms that PWTA is a viable material for cement replacement to produce sustainable concrete.

The primary results obtained in this study demonstrate the great potential of PWTA as an alternative SCM in producing sustainable concrete. This work can be extended by evaluating the performance of PWTA concrete in aggressive environments (sulfate and acid) and under reinforcement corrosion and comparing it with those of other well-known biomass ashes.

Author statement

1. *Muhammad Akbar Caronge*: Conceptualization; Data curation; Formal analysis; Methodology; Roles/Writing - original draft.
2. *M. W. Tjaronge*: Supervision; Conceptualization; Writing - review & editing.
3. *Irwan Ridwan Rahim*: Conceptualization; Methodology; Formal analysis; Writing - review & editing.
4. *Rita Irmawaty*: Formal analysis; Validation; Writing - review & editing.
5. *Franky E. P. Lapian*: Project administration; Resources; Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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