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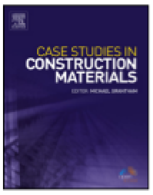
SUBMISSION ID	1251876366	CHARACTER COUNT	28292

Case Studies in Construction Materials 12 (2020) e00325

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm



Case study

Evaluation of sustainable concrete paving blocks incorporating processed waste tea ash

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ARTICLE INFO

Article history:
Received 23 July 2019
Received in revised form 5 December 2019
Accepted 9 December 2019

Keywords:
Sustainable
Concrete
Paving block
Waste tea ash
Cement

ABSTRACT

Agricultural waste is a viable material that can be used as a cement replacement in the cement-based material, which is contributed to reducing the CO_2 emission from cement production. In this study, processed waste tea ash (PWTA) as a cement replacement of paving blocks at dosages of 10 %, 20 %, 30 %, 40 %, and 60 % by weight of cement were investigated for the first time. Several testing were included for the workability, density, compressive and flexural strength, water absorption, acid attack resistance, and microstructure through SEM observation. Test results confirmed that the replacement of cement with PWTA decreased the quality of the paving blocks. Owing to the greater porosity of PWTA, it increases the void within paving blocks, which is associated with a decrease in the paving block properties as indicated by SEM observations. Although the strength of the paving blocks decreased with the PWTA replacements, the paving blocks containing 20 % and 40 % PWTA still met the minimum requirements specified by Indonesian National Standard for Class C (pedestrian areas) and Class D (garden areas), respectively. Therefore, incorporating PWTA as a replacement for cement allowed a more sustainable and low-cost paving block to be produced.

1. Introduction

The paving block is a construction material that is mainly used in streets, driveways, sidewalks, garages, and parking lot. Indonesian National Standard (SNI) 03-0691-1996 [1] defines the paving block as a composite material made from Portland cement or similar hydraulic adhesive materials, water, and aggregate. The increasing demand for paving blocks as a construction material has resulted in increased cement requirements for the manufacture of paving blocks. Reducing the use of cement in the manufacture of cement based materials such as mortar, concrete and paving block can significantly reduce CO_2 emissions from cement production, which results in 0.9 ton of CO_2 for every 1.0 ton of cement [2]. Approximately 8 % of total global CO_2 emissions are originated from cement production [3]. To overcome this problem, a lot of attempt has been made to utilize waste materials and by-products such as fly ash, silica fume, ground granulated blast furnace slag, ceramic waste powder, rice husk ash, palm oil fuel ash, sugar bagasse ash, and incinerator bottom ash as an alternatives to partially replace cement in the cement-based materials [4–10].

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https://doi.org/10.1016/j.cscm.2019.e00325

The majority of previous studies have focused on incorporating waste materials for the replacement of aggregate in paving block production such as recycled demolition aggregates [11], brick aggregate [12], rubber waste [13], recycled cathode ray tube funnel glass [14], and crushed ceramic [15]. Furthermore, few studies have researched incorporating mineral waste materials as a cement replacement in concrete paving block production. Ganjian et al. [16] used by-products and waste materials such as granulated blast furnace slag (GGBS), cement by-pass dust (BPD), run-of-station ash, basic oxygen slag, and plasterboard gypsum as cement replacements. Their test results confirmed that a concrete paving mix containing 6.3 % GGBS, 0.7 % BPD, and 7.0 % Ordinary Portland Cement (OPC) by weight could decrease Portland cement content by 30 % in comparison to the percentage of cement used in factories without having a negative impact on the strength and durability of the paving blocks. Limbachiya et al. [17] studied the replacement of Portland cement with GGBS and silica fume (SF) in paving blocks and found that the cement content can be decreased by 40 % after the incorporation of GGBS and SF, which achieved higher strength than that of the control block made without GGBS and SF. Sadek et al. [18] investigated the mechanical and durability properties of concrete paving blocks incorporating cement kiln dust (CKD). Results showed that up to 40 % CKD could be used to produce environmentally-friendly paving blocks for heavy traffic applications, whereas 60 % CKD blocks were suitable for areas subjected to medium traffic applications such as in city streets. However, incorporating 40 %–60 % CKD is not recommended for applications of blocks in an acid environment. Mashaly et al. [19] studied the effects of marble sludge on the properties of the concrete paving block as a cement replacement at dosages of 0–40 %. They concluded that incorporating marble sludge improved the physical and mechanical properties of the paving block, and up to 20 % replacement fulfilled standard specification limit of concrete paving blocks. Penteado et al. [20] investigated the feasibility of porcelain tile waste replacing the cement in the paving block production. Their test results showed that the 20 % replacement of cement with porcelain tile waste was suitable to produce the paving blocks for heavy vehicle traffic. Jegan & Sriram [21] found that replacing up to 25 % of cement with granite powder achieved higher compressive and flexural strength than conventional paving blocks. In addition, de Azevedo et al. [22] reported that incorporating 40 % granite residues improved technological properties of mortar in the fresh state. Dodoo-Arhin et al. [23] obtained an eco-friendly paving block by incorporating 25 % of calcined red mud as cement replacement in the paving blocks production. Agyeman et al. [24] concluded that recycle waste plastic can be used as an alternative binder in paving blocks which gave higher compressive strength and lower water absorption than control paving blocks. Also, the used of glass waste of 10%–20% as cement replacement in mortar satisfies the rheological properties of mortar for adhesive application [25].

All previous studies have proven that mineral waste materials can be used as cement replacements in the production of concrete paving blocks, which achieved the quality of current standard/code. However, studies on agricultural waste materials as a partial cement replacement for concrete paving block production were not yet reported extensively. Therefore, the present study aimed to investigate the possibility of processed waste tea ash (PWTA) from the tea processing plant industry to be used as a cement replacement in the production of paving blocks. The ashes were obtained by burning processed waste tea under a temperature of approximately 700–800 °C to produce energy for the tea extraction process. Approximately 18,000 tons of ashes are accumulated during tea processing of plants per year [26]. Most of these wastes are disposed in landfills, which could lead to health-related issues and environmental problems. In the present study, PWTA was used as a partial replacement of cement to produce paving blocks under real industrial conditions. Subsequently, paving block properties such as workability, density, compressive and flexural strength, water absorption, acid attack resistance, and microstructures were investigated. The usage of PWTA in paving block production will not only help in solving the environmental problems generated from PWTA disposal but will also reduce the usage of significant quantities of cement in the paving block industry. Therefore, the incorporation of PWTA as novel cement replacement can produce eco-friendly paving blocks.

2. Experimental procedures

2.1. Materials

Portland composite cement (PCC) that conformed to SNI 15–7064 [27] with a specific gravity of 3.08 was used in the present study. Natural river sand with a fineness modulus of 2.77 and a specific gravity of 2.58, respectively, was used as fine aggregate. Crushed stone with specific gravity and maximum size aggregate of 2.83 and 5 mm, respectively, was used as coarse aggregate. The grading curves of the fine and coarse aggregates used are presented in Fig. 1. PWTA was a by-product obtained from small power plants of a tea processing plant in Gowa, Indonesia. As received, PWTA was oven dried at 105 °C for 24 h and then sieved by passing through a No. 80 (300 μm) mesh before using as cement replacement in the paving blocks (Fig. 2).

The physical and chemical compounds of PWTA obtained from X-ray fluorescence (XRF) are presented in Table 1. The PWTA have a specific gravity of 2.05 with maximum particle size of 300 μm. The chemical analysis showed that the main oxides of PWTA were calcium oxide (CaO), silicon oxide (SiO_2), potassium dioxide (K_2O), and iron oxide (Fe_2O_3) which comprised 43.74 %, 49.82 %, 4.04 %, and 1.30 %, respectively. Fig. 3 shows the X-ray diffraction (XRD) pattern of PWTA. It was identified that the phases are $CaCO_3$, SiO_2, K_2O, NaO_3, CaO and Fe_2O_3. The scanning electron micrograph (SEM) image of PWTA is shown in Fig. 4, with the PWTA particles being mainly of an angular and irregular shape with a porous surface structure.

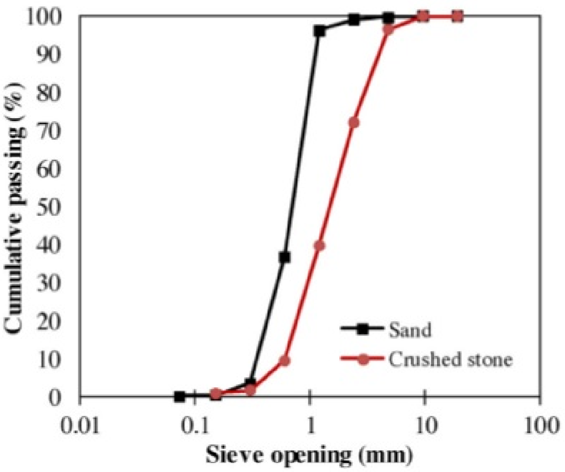


Fig. 1. Sieve analysis of aggregate.

Fig. 2. PWTA after being sieved to 300 μm.

2.2. Specimen preparation

The paving blocks were manufactured in a local factory to study the feasibility of producing paving blocks containing PWTA in real industrial production conditions. The mix proportion of the con[illegible] paving block was based on the manufacturer's recommendation. The ratio of the mix proportion was 1.0:1.1:2.0 of cement, fine aggregate, and coarse aggregate, respectively. PWTA was used to replace 10 %, 20 %, 30 %, 40 %, and 60 % of cement weight and the required water

Table 1
Physical and chemical compounds of PCC and PWTA.

Material	PCC	PWTA
Physical properties		
Specific gravity	3.08	2.05
Max. sizes particles	45 μm	300 μm
Chemical compound (%)		
SiO_2	18.39	43.74
Al_2O_3	5.15	0.46
Fe_2O_3	3.41	1.30
CaO	61.79	49.82
SO_3	1.81	0.32
MgO	0.99	0.11
K_2O	–	4.04
P_2O_5	–	0.92
LOI	4.61	12.40

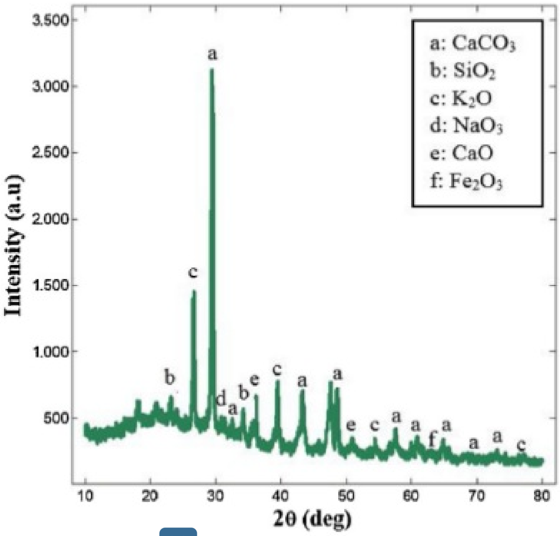


Fig. 3. XRD pattern of PWTA.

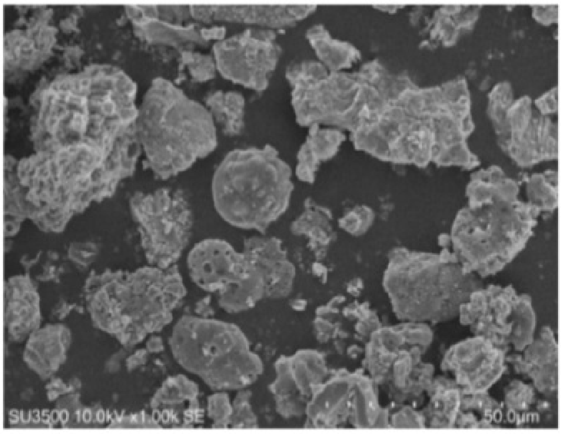


Fig. 4. SEM image of PWTA.

was adjusted to achieve zero slump which is commonly used on the industrial scale. Table 2 shows the mix proportion of the paving blocks. The mixing procedure was as follows: first, the cement/PWTA and fine and coarse aggregates were dry mixed manually. Then, water was added to the mixture and mixing was continued until homogeneous. Finally, the fresh mix was placed into steel molds of 200 mm × 100 mm × 70 mm and compacted using a handy press. Afterward, the blocks were removed from the molds and left in the open air for 24 h before they were cured by sprinkling with water twice a day until the testing age. The procedure of the paving blocks production is depicted in Fig. 5.

Table 2
Mix proportion of paving blocks.

No	Mix ID	Water (kg/m^3)	Cement (kg/m^3)	PWTA (kg/m^3)	Sand (kg/m^3)	Crushed stone (kg/m^3)
1	M0	79.3	396.8	0	436.5	1230.16
2	M10	91.3	357.1	39.68	436.5	1230.16
3	M20	99.2	317.5	79.37	436.5	1230.16
4	M30	146.8	277.8	119.1	436.5	1230.16
5	M40	182.5	238.1	158.7	436.5	1230.16
6	M60	210.3	158.7	238.1	436.5	1230.16

Fig. 5. Procedure for making the paving block (a) mixing; (b) compacting; (c) fresh blocks; (d) curing method.

2.3. Testing methods

2.3.1. Density

The density of the paving blocks was determined by applying the samples into a drying oven at 105 °C for 24 h and then cooled at 25 ± 2 °C for 5 h. Afterward, the samples were weighed. Density was calculated by dividing the weight by the volume of the sample.

2.3.2. Compressive strength

The compressive strength of the blocks was tested at 7 and 28 days based on the methodology described in SNI 03-0691 [illegible] using a universal testing machine. The load was applied to the surface of the block until the failure of the sample, as shown in Fig. 6. Compressive strength was calculated as (Eq. 1).

$$\sigma_C = P/A \quad (1)$$

where σ_C is the compressive strength (N/mm^2), P is the failure load of the specimen (N), and A is the surface area of the applied load (mm^2).

Fig. 6. Paving block under compression.

Fig. 7. Paving block under flexural loading.

2.3.3. *Flexural strength*

The flexural strength test was performed at 28 days in accordance with SNI 03-4154 [28], as shown in Fig. 7. The block sample was placed in the flexural beam apparatus and subjected to a 3-point loading with a clear span of 170 mm. The load was applied to the paving block sample through a steel rod until failure of the sample. The flexural strength of each sample was determined using Eq. 2.

$$\sigma_F = 1.5\,PL/(b^2d) \tag{2}$$

where σ_F is the flexural strength (N/mm^2), P is the failure load of the sample (N), L is the span length (mm); and b and d are the width and depth of the sample (mm), respectively.

2.3.4. *Water absorption*

The water absorption of the samples was determined in accordance with SNI 03-0691 [1] at 28 days. First, the block samples were placed in tap water for 24 h. After removal from the water, the surface water was wiped off the block sample, and the weight was measured (W1). Then, the samples were oven dried at 105 °C until a constant weight (W2) was reached. The water absorption of the paving block was calculated as (Eq. 3).

$$WA = (W1\text{-}W2)/W2 \times 100\% \tag{3}$$

where WA is the water absorption (%), W1 is the wet weight of the paving block (kg), and W2 is the dry weight of the paving block (kg).

2.3.5. *Acid resistance test*

The acid resistance of paving blocks was carried out at 28 days by immersed in a 3 % of H_2SO_4 solution for 56 days as per SNI 03-0691 [1]. After 56 days, the paving blocks were taken out and washed with tap water and kept in the open-air condition until reach a constant weight. Then, the compressive strength of paving blocks was determined by using a universal testing machine.

2.3.6. *Scanning electron microscopy (SEM)*

The microstructural morphology of hardened paving blocks was investigated using SEM Hitachi SU3500. SEM observation was carried on the broken pieces of the paving block M0, and M40, which is obtained after the compressive strength test at 28 days.

3. Results and discussion

3.1. *Workability*

The workability of the fresh paving block depends on the amount of water added into the mix to prevent the block sag after the removal of the molds. As shown in Fig. 8, the water to binder ratio (w/c) increases with an increase in PWTA content. Using 60 % PWTA as a cement replacement increased the w/c from 0.2 to 1.33. The porous surfaces and high specific area of PWTA that absorb much water during mixing can be the reason for the increase in the w/c.

3.2. *Density*

The average densities of the paving blocks at all replacement levels of cement with PWTA are presented in Fig. 9. The density values decreased with increasing PWTA content and it was lower than that without PWTA (M0). The density of the

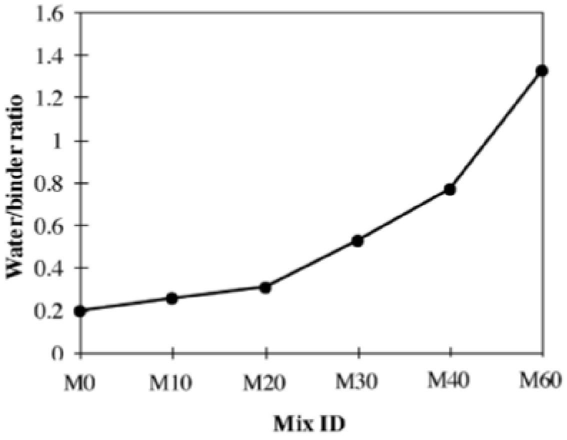


Fig. 8. Water/binder ratio requirement for each mix.

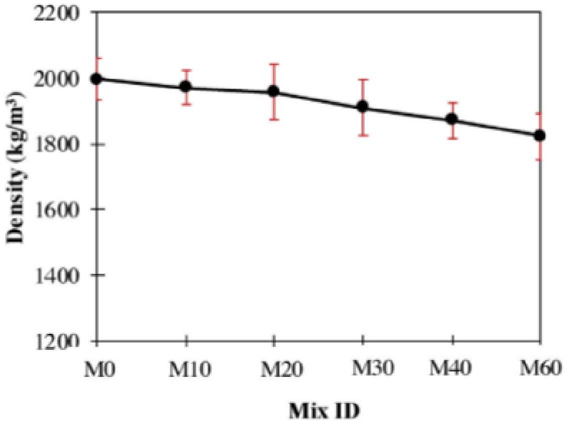


Fig. 9. Density of paving blocks with various PWTA replacements.

paving blocks decreased by 1.3 %, 2.06 %, 4.53 %, 6.72 %, and 9.51 % for M10, M20, M30, M40, and M60, respectively, toward M0. This may due to the lower PWTA density which decreases the density of paving blocks and also the higher content of water in the PWTA paving blocks may generate higher porosity content leaved from water bubble as compared to the paving blocks without PWTA.

3.3. *Compressive strength*

The compressive strength is an important parameter that affects the durability of concrete. Fig. 10 shows the results of 7 and 28 days compressive strength values of the paving blocks. The compressive strength of paving blocks increased with curing time and decrease by increasing the percentage of PWTA as a partial replacement of cement. The compressive strength of the control paving block (M0) was 10.2 MPa at 7 days and 19.81 MPa at 28 days. The compressive strength of the paving blocks M10, M20, M30, M40, and M60 containing PWTA were 8.44, 7.61, 5.84, 4.65, and 3.22 MPa at 7 days respectively, and 15.46, 14.12, 12.10, 10.24, and 7.01 MPa at 28 days, respectively. The high w/c ratio related to the higher porosity content within the hardened cement based material and caused poor interfacial bonding between cement paste and aggregate [18,29]. Therefore, the compressive strength of the paving blocks decreased with increases of PWTA content as the cement replacement. Another possible reason for the reduction in compressive strength of the paving blocks is due to the porous and coarser particle sizes of PWTA. Decreasing the particle sizes can improve the fineness of pozzolanic materials, which contributed to the strength development by acting as a micro-filler and enhancing the pore structure of the cement matrix [30,31]. Likewise, the coarser particles of PWTA (300 μm) resulted in larger voids that led to the decreased compressive strength of the paving block [32,33].

Indonesian standard SNI 03-069 [1] requires a minimum compressive strength of paving blocks at 28 days to be 12.5 MPa and 8.5 MPa for Class C (pedestrian/sidewalks) and Class D (garden application), respectively. The paving blocks prepared up

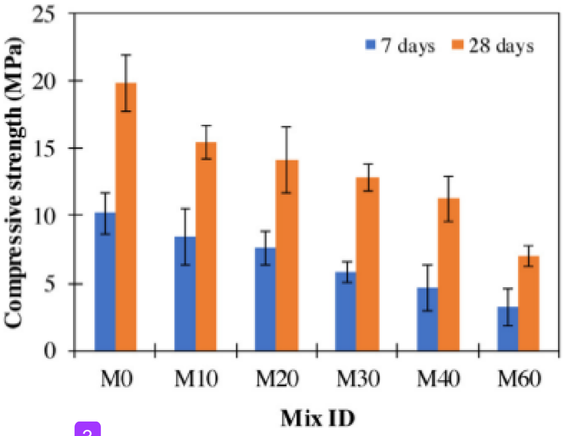


Fig. 10. Compressive strength of the paving block at 7 and 28 days.

to 20 % PWTA met the requirements for pedestrian/sidewalks application and for garden application up to 40 % PWTA replacement was acceptable.

3.4. Flexural strength

The flexural strength of the paving blocks at 28 days is presented in Fig. 11. A similar trend obtained in the compressive strength that for the flexural strength values of the paving blocks. The replacement of cement with PWTA reduced the flexural strength of the paving block. As shown in Fig. 11, the flexural strength of M10, M20, M30, M40, and M60 was approximately 5.03 %, 17.98 %, 26.72 %, 37.44 %, and 53.69 % lower, respectively than that of M0 at 28 days.

Fig. 12 shows the relationship between flexural strength and compressive strength of paving blocks at 28 days. Flexural strength increased with an increase in compressive strength. A previous study by Wongkeo et al. [34] also concluded that the flexural strength had a direct relationship with the compressive strength.

3.5. Water absorption

Water absorption of hardened concrete is related to the nature of the pore system within the hardened concrete. Although aggregate also contains pore, it is usually discontinuous. Aggregate particles are enveloped by a cement paste, which is the only continuous phase in concrete so that the pores in aggregate do not contribute to the water absorption of concrete. Therefore, the influence of aggregate is very small [35].

The water absorption of paving blocks is presented in Fig. 13. The water absorption values increased with increases in the PWTA content. This may be attributed to the porous nature of the paving blocks containing PWTA compared to the control sample (M0). Water absorption was found to be 0.64 %, 4.64 %, 13.14 %, 16.37 %, and 20.75 % higher for paving blocks M10, M20, M30, M40, and M60, respectively, than that of M0. The water absorption from test result was in line with the density.

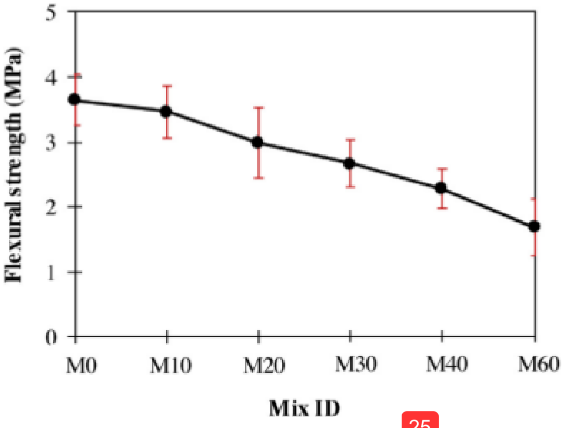


Fig. 11. Flexural strength of paving block at 28 days.

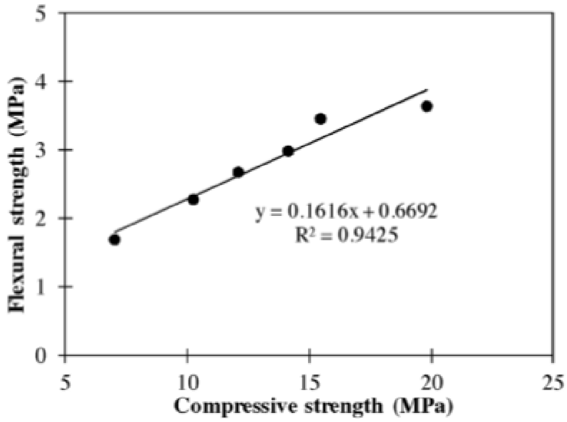


Fig. 12. Relationship between flexural and compressive strength of paving block at 28 days.

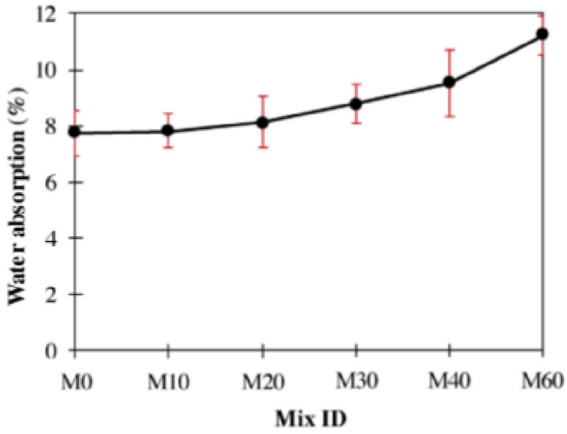


Fig. 13. Water absorption of paving blocks at 28 days.

The higher water content needed to produce PWTA paving blocks resulting in the lower density and higher water absorption due to the increased voids within PWTA paving blocks. The increased absorption value causes the aggressive solution easily penetrates the hardened matrix, which leads to a greater volume of the matrix being attacked by aggressive ion [18].

According to SNI 03-0691 [1], paving blocks with water absorption less than 8 % and 10 % are classified as Class C (for pedestrian/sidewalk application) and Class D (for garden application), respectively. Therefore, paving blocks with 10 % PWTA can be used for pedestrian/sidewalk application, and up to 40 % PWTA for garden application if water absorption is a concern.

3.6. Acid resistance test

Fig. 14 shows the compressive strength of the paving block after kept in air-conditioned laboratory and in a 3 % H_2SO_4 solution for 56 days. For specimens kept in an air-conditioned laboratory, it was observed that the compressive strength of paving blocks M0, M10, M20, M30, M40, and M60 increased by 20.55 %, 17.7 %, 12.89 %, 10.64 %, 11.72 %, and 10.13 %, respectively when compared to the compressive strength at 28 days. This is probably due to the continuous hydration by the effect of moisture available in the laboratory [18]. However, their compressive strength decreased by 9.34 %, 10.74 %, 12.40 %, 10.49 %, 24.14 %, and 20.26 % respectively, after 56 days exposure to 3 % H_2SO_4. It can be confirmed that the higher the PWTA content, the higher the compressive strength loss. This attributed to the high porosity of paving block incorporating PWTA, which facilitates the penetration of acid ion into the specimen and consequently increases the rate of acid attack [18]. This is in line with the result of water absorption.

3.7. Scanning electron microscopy (SEM)

The SEM observations were carried out on the paving block without PWTA (M0) and 40 % PWTA replacement (M40) at 28 days. As shown in Fig. 15, a compact formation of binder matrix was clearly seen for M0 specimen. However, the

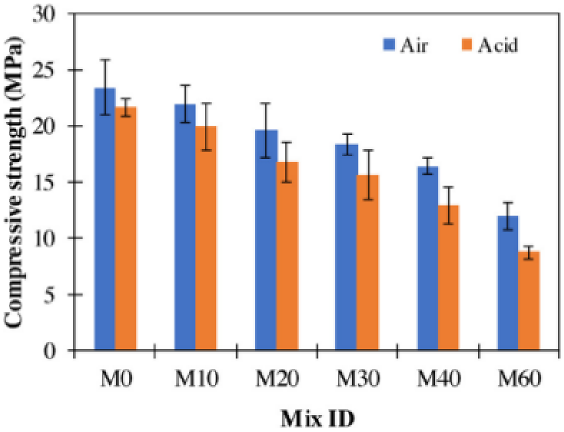


Fig. 14. Compressive strength of the paving block kept in laboratory air condition and immersed in a 3 % H_2SO_4 solution for 56 days.

microstructures of M40 are more porous than M0. This indicated that the increase in the quantity of PWTA results in larger voids in the paving blocks microstructure. The results are in agreement with the properties of paving blocks discussed earlier.

3.8. Carbon emissions and cost benefits of using PWTA

The utilization of waste materials as a cement replacement in the concrete industry provides significant environmental benefits, such as reduced CO_2 emission. The present study estimated the CO_2 emissions of each concrete mixture containing PWTA as a cement replacement. Estimation of CO_2 emissions was carried out based on per cubic meter of concrete, which has been commonly used by previous researchers to estimate the CO_2 emissions of concrete [36–38]. The CO_2 emission factors of the mixture components (water, cement, PWTA, sand and crushed stone) were based on previous research works and databases [37,39]. Fig. 16 shows the estimated CO_2 emission due to the incorporation of PWTA as a cement replacement per cubic meter of concrete for each mix. Obviously, replacing cement with PWTA can reduce CO_2 emissions, and it depends on the amount of PWTA used. It was observed that mix M0 with 100 % cement generated 369.42 kg/m^3 CO_2 emissions. The replacement of cement by 40 % PWTA (M40) reduced the CO_2 emissions by approximately 66.65 % compared to M0 for production per cubic meter of concrete paving blocks. The use of PWTA as a cement replacement is not only helpful for reducing the CO_2 emissions but also for avoided landfilling associated with disposal of this waste material.

Fig. 17 presents a comparison between cost and compressive strength of paving blocks with PWTA at 28 days. PWTA is a free waste material. Therefore, it will reduce the cost of production of the paving blocks. In the local market of Indonesia, the price of cement is approximately 2000 IDR/kg. If the production cost of paving block is 695,111 IDR/m^3, as shown in Fig. 17, the replacement of cement by 10 %, 20 %, 30 %, and 40 % of PWTA reduced the cost of producing the paving blocks to 654,486 IDR/m^3, 613,861 IDR/m^3, 573,236 IDR/m^3, and 532,611 IDR/m^3, respectively, with the compressive strength still within the requirement limits of the paving block application. Overall, this study confirmed the potential use of PWTA to produce a more sustainable and low-cost construction material.

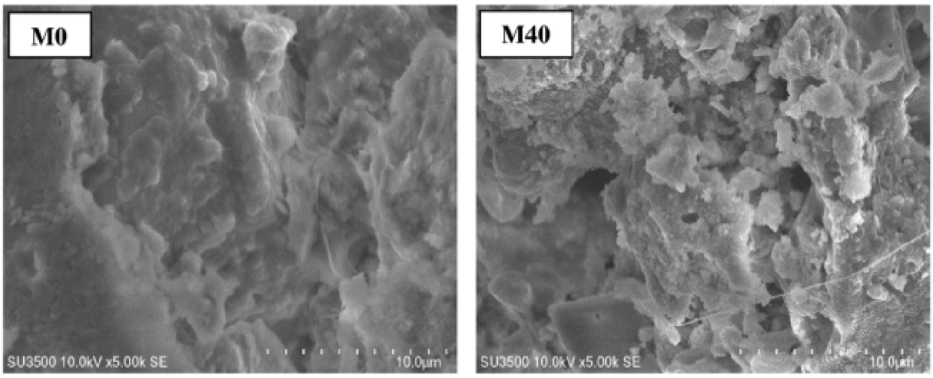
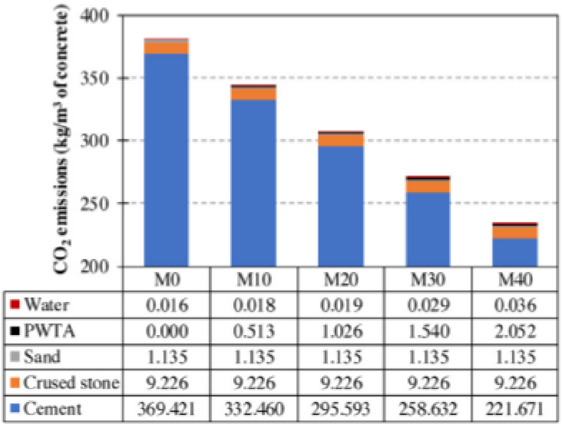


Fig. 15. SEM images of M0 and M40 specimen at 28 days.



	M0	M10	M20	M30	M40
🟥 Water	0.016	0.018	0.019	0.029	0.036
■ PWTA	0.000	0.513	1.026	1.540	2.052
▨ Sand	1.135	1.135	1.135	1.135	1.135
🟧 Crused stone	9.226	9.226	9.226	9.226	9.226
🟦 Cement	369.421	332.460	295.593	258.632	221.671

Fig. 16. CO$_2$ emissions for each mixes.

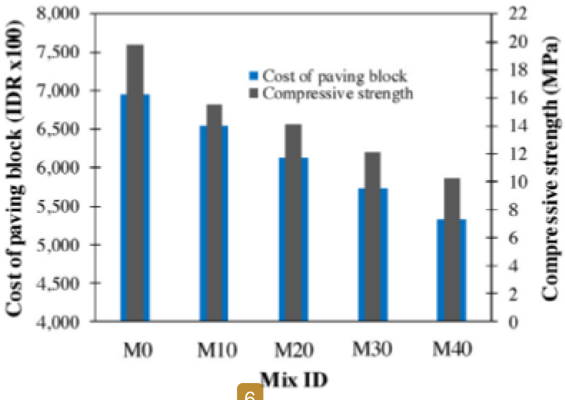


Fig. 17. Comparison between cost and compressive strength of paving blocks at 28 days.

4. Conclusions

The present study utilized PWTA as a replacement for cement to produce paving blocks. The results showed that the porous surface of PWTA increased the water to binder ratio of paving block with increasing the PWTA content as a cement replacement. The density of the PWTA paving blocks decreased as the percentage of cement replacement increased because the PWTA had a lower density than that of the cement. Increased PWTA content decreased the paving block quality in terms of compressive strength, flexural strength, water absorption, and acid resistance due to the increase of voids within paving blocks. Microstructures investigation with SEM revealed that the increase of PWTA content produces larger voids, which significantly affected the quality of the paving block.

The results of compressive strength and water absorption showed that the replacement of cement with up to 40 % PWTA satisfied the requirement of Class D (for garden application) paving block specified by Indonesian National Standard. The incorporation of PWTA as a replacement for cement in paving blocks could help decrease CO$_2$ emissions from cement production and allow the production of a more sustainable and low-cost paving block.

Declaration of Competing Interest

The authors declare no conflict of interest.

Acknowledgments

The authors would like to thank Rino Hidayat, ST for his assistance in the experimental program.

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