Mechanical Properties and Environmental Impact Assessment of Eco-Friendly Pervious Pavement Blocks Containing High-Volume Fly Ash

Steve Supit[1], Kornkanok Boonserm[2], Priyono[3]
1 Civil Engineering Department, Manado State Polytechnic, Indonesia
2 Department of Applied Chemistry, Rajamangala University of Technology Isan, Thailand
3 Mechanical Engineering Department, Manado State Polytechnic, Indonesia

石炭火力発電で発生する微粒子状の灰fly ashはセメントに混ぜるなどして再利用され、セメント業界の二酸化炭素排出削減に貢献している。では、その効果を最大化するにはどうすればいいか。その課題を探った。

Abstract

This study aims to experimentally investigate the potential use of supplementary cementitious materials (SCMs) to improve the characteristics of porous pavement blocks while providing sustainable solutions for stormwater runoff management and the reduction of its carbon footprint. Fly ash, an abundant industrial solid waste that is often used in some Asian countries like Japan, China, Thailand, and Indonesia, was utilized in this study. It was used to replace cement at high-volume to form pervious pavement blocks with a water to binder (cement + fly ash) ratio of 0.3 and a cement: coarse aggregate ratio of 1:3. The environmental impact assessment was calculated based on the mechanical performance value of the CO_2 emission intensity of each material based on the Japan Society of Civil Engineers, Ministry of Health, Labor, and Welfare standard. The results show a promising improvement in the properties of pervious pavement blocks when using high-volume fly ash as a cement replacement based on the compressive strength, flexural strength, and infiltration rate tests. The reduction of CO_2 emissions can also be confirmed, making this product one solution in the construction sector to support practical pathways toward carbon neutrality in Asian countries.

Keywords pervious pavement block, fly ash, environmental assessment, flexural, compressive, infiltration

Introduction

According to the Statistical Review of World Energy, Southeast Asian countries (Malaysia and Indonesia) accounted for 6.3% and 7.6% of the world's carbon dioxide (CO_2) emissions, respectively. China and Japan lowered their emissions by -0.7 and 1.5% in 2016, respectively, in contrast to 2015 (Sharvini et al., 2018). Sustainable infrastructure refers to construction that is environmentally friendly throughout the entirety of its lifecycle, incorporating fiscal, cultural, and institutional aspects. The infrastructure should be designed to endure long periods without collapsing or deteriorating, minimizing the need for major repairs. The construction materials sector is pushing the worldwide market to create inventive types of concrete that exhibit enhanced sustainability and a more environmentally beneficial life cycle. In 2018, this industry contributed 36% of the worldwide energy consumption and 39% of carbon dioxide emissions, leading to global resource depletion (Olagunju & Olanrewaju, n.d.). International collaboration and partnership are necessary for reducing carbon pollution in Asia due to the global implications of climate change. The Paris Agreement and similar initiatives offer a system for countries to collaborate to reduce emissions and adjust to the effects of climate change. As the purpose set by the UN (United Nations) Climate Change is to restrict global warming to 1.5°C, the release of greenhouse gases needs to reach its highest point before 2025 and decrease by 43% by 2030. Asia's substantial contribution to global greenhouse gas emissions is mainly attributed to its fast industrialization, rising demographics, and significant reliance on fossil fuel and coal for energy consumption.

In construction areas, cement production is considered the main contributor to carbon dioxide emissions on Earth. Substituting cement is the most efficient way to rapidly reduce carbon dioxide emissions. Materials like fly ash, silica fume, sludge, and calcinated natural kaolinitic clays are sustainable alternatives for achieving this goal (Ahmed & Kamal, 2022) (Langga Chandra Galuh et al., 2022). It was also explained that replacing a portion of cement with that substance reduces the need for Portland cement, hence decreased quarrying, combustion of fuel, and carbon emissions. Maddalena et al. (2018) also claimed that pozzolanic material can reduce carbon emissions by 23 - 55% compared to Portland cement. Furthermore, using these materials is more cost-effective than applying cement only (Teixeira et al., 2016).

Pervious Block containing Fly Ash

Pervious concrete can be defined as a particular type of concrete consisting of cement, coarse aggregate, little to no fine aggregates, additives, and water that is usually used for improving the ecological environment in terms of soil and water quality, protecting groundwater resources, and managing stormwater runoff (Maguesvari, 2017). Compared to conventional concrete, pervious concrete is more permeable with a pervious structure (15%-30% per volume) that allows the water to penetrate through the concrete matrix, offering sustainable drainage solutions. Some significant factors that generally influence the performance of pervious concrete are the water/cement ratio, the aggregate sizes, the aggregate: cement ratio, and the void volume. Regarding the benefits of pervious concrete, some disadvantages have been discussed about the characteristics of typical pervious concrete, such as the limited bond strength between the aggregates, the risk of clogging by organic and inorganic materials, and the low durability resistance (Zhong & Wille, 2015). These issues have initiated more experimental work to enhance the properties of pervious concrete, for example, by partially replacing cement with various supplementary cementitious materials like natural pozzolans and byproduct materials. One of the byproduct materials that can be used to replace cement partially in standard concrete is fly ash.

According to ASTM C 618 (ASTM C618-17a, 2017), fly ash is a finely divided residue resulting from ground or powdered coal combustion. As a fuel coal combustion product composed of glassy particles, processed fly ash is effective at acting as a pozzolan material and contributes to the concrete's performance with a better resistance to durability concerns such as water absorption, alkali-silica, chloride diffusion and corrosion resistance (Malvar & Lenke, 2006; Saraswathy & Song, 2006; Xu et al., 2010) In addition, it increases sustainability and is appropriate for producing high mechanical strength at a low cost. Typically, fly ashes are Class F and Class C. Class F is produced from coal by burning bituminous and anthracite at a higher heat. On the other hand, Class C is processed by burning lignite and sub-bituminous coal, which contains a higher amount of carbon than Class F. The utilization of fly ash has made some progress in addressing the challenges of sustainable construction. Due to the spherical shape and glassy particles of fly ash, the water content can be reduced, offsetting the reduction of early-age strength. In addition, fly ash involves pozzolanic activity, which is attributed to the presence of SiO_2 and Al_2O_3(Bendapudi & Saha, 2011). In a pozzolanic reaction, it reacts with calcium hydroxide, reducing the risk of leaching calcium hydroxide during cement hydration to form additional Calcium Silicate Hydrate (CSH) and Calcium Aluminate Hydrate (CAH), which are influential in forming a denser matrix leading to higher strength and better durability. For example, due to a sulfate attack and alkali-silica reaction resistance (Chindaprasirt et al., 2009; Malvar & Lenke, 2006).

Previous investigations into fly ash (FA) as an additional cementitious substance and the environmental assessment (Lee et al., 2020) reported that as the quantity of pulverized coal combustion ash (PCC ash) use has escalated, the global warming potential (GWP) and ozone layer depletion potential (ODP) have decrease by

17.26 kg CO_2 eq/m3 and 3.0 × 10−6 kg CFC-11 eq/m3, respectively. The study concludes that substituting PCC ash for standard Portland Cement in the same concrete mix ratios effectively minimizes adverse environmental effects. In addition, other studies on ash waste correlatives with carbon emission disclosure (CED) and Global Warming Impact (GWI) (Lovecchio et al., 2020) have found that adding 40% and 60% FA to concrete considerably lowers the CED by about 16% and 24%, respectively. The GWI of the mix 0% is 469 kg CO_2 eq, which can be reduced by 32% to 48% using 40% and 60% concrete mixes (319 and 244 kg CO_2 eq, respectively).

Eco-friendly construction in Asian Countries

Sustainable construction focuses on implementing waste to generate environmentally friendly products that address interconnected environmental issues, aiming to positively impact air and soil quality. The utilization of green construction components can improve the atmosphere as well as building efficiency, which benefits the tropical environment, biology, and technology. An alternative solution classified as green construction where fly ash is used waste is permeable blocks, providing a solution to CO_2 pollution by preventing the construction of impermeable surfaces that hinder natural water infiltration into the soil. The Environmental Protection Agency (EPA) validates pervious concrete for pollution control and storm management capabilities (A, 2008). A significant volume of rainfall collects on impermeable surfaces like parking lots, driveways, walkways, and streets instead of being absorbed into the ground. It ultimately results in an environmental imbalance. This solution enhances and balances the surface temperature, and promotes green open spaces, as well as the green basic coefficient to aid in purifying the atmosphere by decreasing the surplus accumulation of carbon through fostering greenery in urban regions (Fadloli et al., 2023).

The advancement of eco-friendly construction in Asian countries demonstrates the growing realization of responsibility for the environment and a dedication to constructing a healthier future for all. Singapore is spearheading the development of green construction in Southeast Asia (Lai et al., 2023). The installation of pervious pavement blocks at the Tianjin Univ. institution in China (Chandrappa & Biligiri, 2016) revealed that the performance of the pervious blocks decreased the highest flow by 28.7% and overall runoff by 35.6%. The results show that the type of pervious pavement, the state of draining in porous surfaces, and the water quantity at the start of the rainstorm all significantly influenced the hydrological impact of permeable roads on flood reduction. Another country in Southeast Asia (Malaysia) is also integrating permeable pavers into urban redevelopment projects and green infrastructure efforts to mitigate flooding and heat-related urban impacts. Pervious block surfaces are being implemented in public places, residential developments, and commercial areas in urban centers such as Kuala Lumpur and Penang (Abustan et al., n.d.).

Research significance

The significance of this research is to evaluate the performance of pervious pavement blocks based on their strengths and properties, and to identify their performance in connection to the environmental side of things when using fly ash at a high volume. These findings will provide a platform to standardize the implementation of high-volume fly ash as a byproduct material to support green and sustainable construction, especially in Asian countries.

Materials and experimental methods

In this experiment, the primary binders are Portland Composite Cement (PCC) blended with fly ash type C sourced from the Steam Power Plant in Amurang, North Sulawesi Province. As seen in Table 1, the fly ash has a CaO content of 28.13%, with a silicate content of 18.77%. From this percentage, it can be expected to form concrete products that have a lower carbon content and higher mechanical properties in comparison to the typical standard concrete containing 100% cement. In the production of pervious pavement blocks, natural coarse aggregate of two different sizes, i.e. a maximum size of 10mm (Type A) and 20mm (Type B). The type A mixtures were designed to have a ratio of cement+binder:

coarse aggregate: fine aggregate of 1:2:1 and a water to binder ratio = 0.3. Type B mixtures were produced with a cement+binder: coarse aggregate of 1:3 with the same water-to-binder ratio as Type A. In this mixture, no fine aggregate was considered. The binder involves the combination of cement and fly ash with a percentage replacement of 40%, 50%, 60%, and 70% by wt. of cement. Superplasticizer type F was also used as a chemical admixture to maintain the consistency of the pervious pavement blocks during mixing. For specimen size, type A and type B mixtures were produced with 80mm and 60mm thickness sizes, respectively. The mixture proportions used in this research are tabulated in Table 2. The specimens were produced using a paving block-making machine in collaboration with a paving block manufacturer company.

Table 1. Chemical composition of PCC and Fly Ash (%)

Chemical Analysis	PCC	Fly Ash
SiO_2	8.43	18.77
Al_2O_3	1.65	6.89
Fe_2O_3	4.81	21.8
CaO	73.12	28.13
MgO	-	4.65
K_2O	-	1.38
Na_2O	-	7.41
SO_3	2.71	6.65

The specimens were then tested under laboratory conditions to define the compressive strength, flexural strength, void ratio, and infiltration rate after curing for the 7th and 28th days. The tests were conducted based on the American Society for Testing and Materials (ASTM), and Japan Society of Civil Engineers (JSCE) standards. Figures 1 and 2 show the testing of the samples on their compression, bending, and infiltration rates.

Table 2. Mixture proportions (kg/m^3)

No	Mix Code	PCC	FA	CA	S	W	SP	Mix Type
1	C100	400	0	800	400	120	2	A
2	FA40	240	160	800	400	120	2	A
3	FA50	200	200	800	400	120	2	A
4	FA60	160	240	800	400	120	2	A
5	C100	400	0	1200	0	120	2	B
6	FA40	240	160	1200	0	120	2	B
7	FA50	200	200	1200	0	120	2	B
8	FA60	160	240	1200	0	120	2	B
9	FA70	120	280	1200	0	120	2	B

Notes: C100 = cement 100%; PCC = Portland Composite Cement; FA = Fly Ash; CA = Coarse Aggregate; S = Sand; W = Water; SP = Superplasticizer

(1) (2)

Fig. 1. Type A (1) Compressive strength, and (2) Infiltration

(1) (2)

Fig. 2. Type B (1) Pervious paving blocks casting process, and (2) Flexural Strength Test

Results and discussions

Compressive strength

The compressive strength test was conducted to evaluate the influence of high-volume fly ash when replacing cement in pervious concrete blocks. For the type A samples, the highest strength value was by the sample containing 30% fly ash by wt. of cement, i.e. 17 MPa and 23 MPa at 7 and 28 days, respectively (see Figure 3).

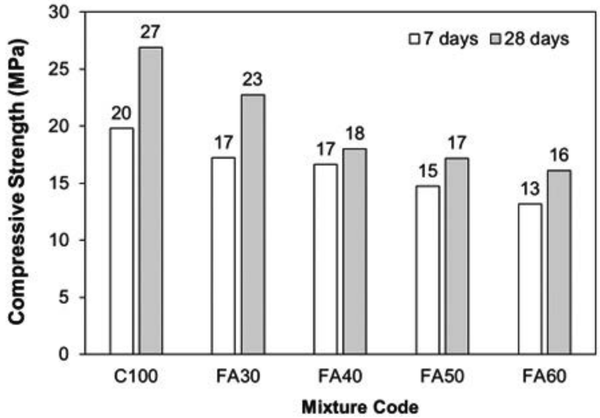

Fig. 3. Compressive strength results on mixture type A

The 28th-day strength was 14% lower compared to the normal pore block without fly ash addition or 100% cement. The compressive strength of the samples with 40%, 50%, and 60% showed no significant difference at 7 and 28 days. Based on the results, the FA30 sample can be categorized as quality B, which can be used for parking lots according to the Indonesian National Standard (SNI 03-0691-1996), as seen in Table 3. Compared to the results of the type B samples, the samples without fine aggregate and a larger maximum size of coarse aggregate were not effective at improving the compressive strength with the maximum strength being obtained by the sample containing 60% fly ash replacement, i.e. 9 MPa at 28 days. The strength then dropped to 6 MPa when the volume of fly ash replacement was increased to 70% (see Fig. 4).

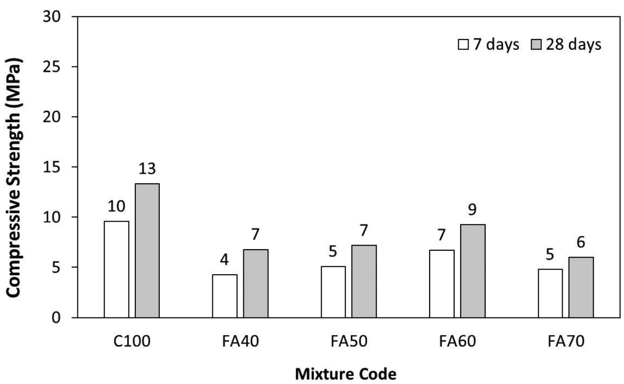

Fig. 4. Compressive strength results on mixture type B

Since the maximum strength of the compression load was only 9 MPa, this type of mixture can only be applied to gardens or other applications that do not require a load that is too heavy. Overall, the results conclude that to improve the properties of the pervious pavement block, fine aggregate can be added while using smaller coarse aggregate. In this case, the percentage of fly ash can be recommended to be 40 to 60% cement replacement.

Table 3. Physical properties of the paving block based on SNI 03-0691-1996

Quality	Compressive strength (MPa)		Maximum absorption
	Average	Min	(%)
A	40	35	3
B	20	17	6
C	15	12,5	8
D	10	8,5	10

Flexural strength

Figures 5 and 6 show the flexural strength results of the pore blocks containing high-volume fly ash on different type of mixtures after testing on the 7th and 28th day.

The results show that among the samples containing fly ash, the highest flexural strength in sample type A was the pervious pavement block sample containing 40% fly ash (FA40) with strength values of 3.4 and 3.7 MPa at 7 and 28 days, respectively. The increase in fly ash volume reduced the resistance performance of the pervious pavement blocks for flexural load. In sample type B, no significant difference was found in flexural strength if the specimens contained a high volume of fly ash. However, the flexural strength of all samples was still in the range of the typical strength of pervious concrete, i.e. 1-3.7 MPa. Using smaller particle sizes of coarse aggregate with fine aggregate improved the strength of the pervious pavement blocks, with the maximum percentage of fly ash at 40%. It was interesting to note that the specimens containing a larger size of coarse aggregate tended to have comparable flexural strength, although the content of fly ash increased by up to 60%. This phenomenon was also found in the compressive strength results that indicated that the coarse aggregate's size influenced the strength properties of pervious pavement blocks, even with a higher percentage of fly ash and without the use of fine aggregate. In this case, the larger size of the coarse aggregate was proportional to the paste volume, increasing the binding properties to resist the bending stress to which it was subjected. A similar observation was also reported by Yu et al. (2019). In this study, they also found that an increase in aggregate size (over 7 mm) increased the compressive strength rapidly. They also mentioned a further improvement of strength can be achieved by increasing the paste thickness up to 1.15mm.

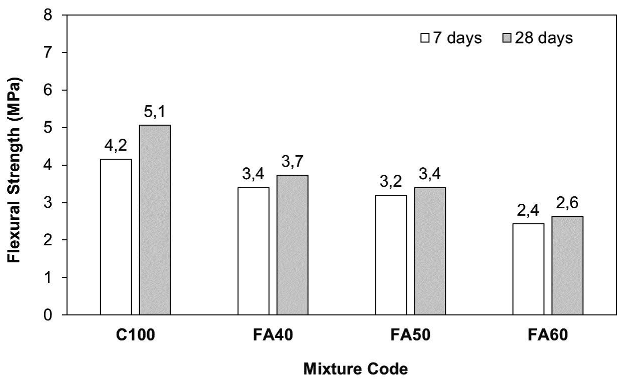

Fig. 5. Flexural Strength results on mixture type A

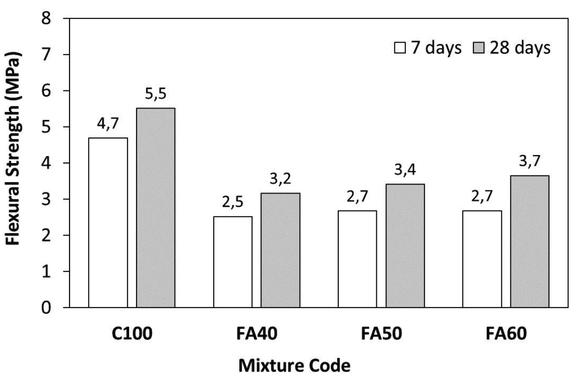

Fig. 6. Flexural Strength results on mixture type B

Void ratio

Further investigation of the void ratio was made on the pervious pavement blocks using larger coarse aggregate with no fine aggregate. It can be seen in Fig.7 that the specimens containing fly ash had a higher total porosity compared to the normal pervious block without fly ash.

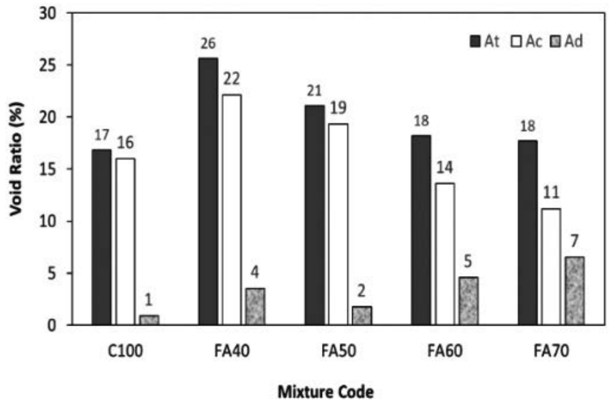

Fig. 7. Void ratio results on different type of mixtures

Increasing the fly ash content reduced the percentage of voids due to the increase in paste volume. The continuous voids in the pervious pavement blocks also showed the same trend with the reduction of total voids (At) when increasing the fly ash volume. The higher the percentage of continuous voids (Ac), the higher permeability expected. On the other hand, the discontinuous void (Ad) percentages that appeared in high-volume fly ash, i.e. FA60 and FA70, were higher than for the FA40 and FA50 specimens. This means that the degree of compaction was greater when using a higher volume of fly ash in the mixtures, resulting in an improved density for the pervious pavement blocks. However, the poor pozzolanic activity of fly ash resulted in reducing the compression load resistance. This is a common behavior due to using high-volume fly ash that should be minimized by optimizing the utilization of ternary blended systems, for example, using nanoparticles or chemical additions. This modification could promote a pozzolanic reaction and facilitate the late strength development of high-volume fly ash (Shaikh et al., 2014; Supit et al., 2014).

Infiltration Rate

The infiltration rate test was conducted on C100 containing 100% cement and FA60 containing 60% fly ash as a cement replacement. This test examined the ability of water to enter the specimens and flow into the soil. FA60 was selected among the other variations since this sample obtained a higher strength compared to the other percentages of cement replacement. The results in Figure 8 clearly show that using 60% fly ash as a cement replacement reduced the ability of the water to penetrate the specimens from 5.37 mm/hour to 2.71 mm/hour, which is 50% lower than the C100 sample.

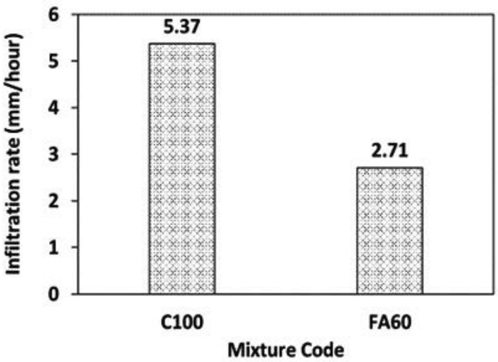

Fig. 8. Infiltration results of C100 and FA60

Environmental assessment

The most appropriate parameters used to assess the ecological properties of concrete were carbon footprint and energy demand (Habert et al., 2020). In this case, the environmental impact assessment was calculated based on the compressive strength performance and environmental impact evaluation value following the equation developed by Fantilli & Chiaia (2013) as follows:

$MIx = MI/MIinf$ (1)

$EIy = EIsup/EI$ (2)

$EMI = MI/EI$ ($MPa\times m^3/kg$) (3)

where MIinf is the reference compressive strength, MI is the compressive strength (MPa), EIsup is the reference CO_2 emissions, and EI is the CO_2 emissions (kg/m^3). The definition of MI is based on concrete strength and can also include other mechanical properties of concrete structures.

CO_2 emissions can be calculated using an equation where E is CO_2 emissions (kg/m^3), w is the unit mass of each material (kg/m^3), and e is the CO_2 emissions intensity of each material (kg/t).

$E = S (w \times e / 1000)$ (4)

The CO_2 emissions based on the JSCE 2004 standard are shown in Table 4, while Figure 9 shows the relationship between the intensity of the CO_2 emissions and compressive strength performance.

Table 4. CO_2 emissions based on JSCE 2004 standard

Materials	CO_2 emissions intensity (kg/t)
Cement	766.6
Fly Ash	19.6
Superplasticizer	100
Coarse Aggregate	2.9
Fine Aggregate	4.7

Figure 9 shows the relationship diagram between MI and EI where the lower area represents compressive strength performance, and the higher area is the ecological impact. In this diagram, the compressive strength results were selected based on the strength performance of mixtures containing 40%, 50%, and 60% of fly ash compared with control mixture.

The diagram can be divided into four different zones representing the performance of each mixture type of permeable pavement block. Zone 1 indicates low compressive strength–low ecological performance, Zone 2 indicates high compressive strength–low ecological performance, Zone 3 indicates high compressive strength–high ecological, and Zone 4 indicates low compressive strength–high ecological performance. Based on the plotting, the performance of the permeable pavement blocks using high-volume fly ash are in Zone 4, indicating that high ecological performance can be expected. However, modification to the mixture containing high-volume fly ash is still necessary to help it become a more sustainable permeable pavement product.

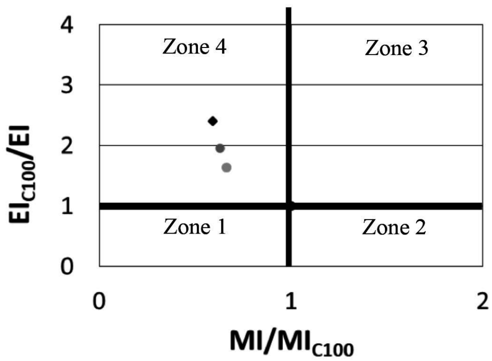

Fig. 9. Environmental assessment of different type of mixtures

Conclusions

The mechanical properties and environmental assessment of pervious pavement blocks containing high-volume fly ash have been examined. The results can be summarized as follows:

- Samples that do not contain fine aggregates or coarse aggregates with a maximum size don't act to increase the compressive strength. Sample FA30 had the highest compressive strength categorized as quality B, which means it can be used for parking lots.
- The data showed that smaller coarse aggregates can be mixed with fine aggregates to improve the pervious pavement blocks. The increase in fly ash volume decreased the tensile effectiveness of the pervious pavement blocks under flexural strain.
- Despite a high-volume fly ash concentration of up to 60%, the pavements with larger rough aggregate sizes had a comparable flexural strength. The sample blocks with fly ash had a higher overall porosity than the samples without ash. Increasing the fly ash content reduced the percentage of voids due to the increased paste volume.
- Based on the ecological performance, the use of high-volume fly ash could provide high ecological performance but still be low in compressive strength. Therefore, modification by adding another pozzolanic material such as metakaolin or silica fume in nano form can be considered for further development regarding the use of high-volume fly ash as a construction material.
- The implementation of green technology necessitates specialized knowledge due to its higher level of complexity compared to traditional procedures. Construction businesses must follow additional regulations and requirements to ensure a solid understanding of implementing environmentally friendly practices, which can extend the construction process due to the need for extra steps.

Acknowledgement

The authors wish to thank the Atsumi International Foundation and Manado State Polytechnic for the grants and technical support during the research.

Conflicts of interests

The authors declare that they have no conflicts of interests.

Data availability

The data that support the findings of this study are available on request from the corresponding author, Steve Supit. The data are not publicly available due to their containing information that could compromise the privacy of research participants.

Funding

The publication of this research was supported by Atsumi International Foundation through Asia Future Conference scholarship year 2024.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Steve Supit, Kornkanok Boonserm and Priyono. The first draft of the manuscript was written by Steve Supit and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate

Not applicable in this section

References

A, R. B. (2008). Green Pervious Concrete. *International Journal of Advances in Engineering and Management (IJAEM*, *2*(1), 1107. https://doi.org/10.35629/5252-45122323

Abustan, I., Hamzah, O., & Rashid, A. (n.d.). *REVIEW OF PERMEABLE*

PAVEMENT SYSTEMS IN MALAYSIA CONDITIONS.

Ahmed, S., & Kamal, I. (2022). Green Conductive Construction Materials Toward Sustainable Infrastructures. *ECS Transactions*, *107*(1), 2139–2153. https://doi.org/10.1149/10701.2139ecst

Bendapudi, S., & Saha, P. (2011). Contribution of Fly ash to the properties of Mortar and Concrete. *International Journal of Earth Sciences and Engineering*, *04*, 974–5904.

Chandrappa, A. K., & Biligiri, K. P. (2016). Comprehensive investigation of permeability characteristics of pervious concrete: A hydrodynamic approach. *Construction and Building Materials*, *123*, 627–637. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2016.07.035

Chindaprasirt, P., Kanchanda, P., Sathonsaowaphak, A., & Cao, H. (2009). Sulfate resistance of blended cements containing fly ash and rice husk ash. *Construction and Building Materials*, *21*, 1356–1361. https://doi.org/10.1016/j.conbuildmat.2005.10.005

Fadloli, L., Arifin, H. S., & Ridwan, W. A. (2023). Study on green concrete (porous concrete) sustainability to support sustainable construction in Indonesia. *Jurnal Pengelolaan Sumberdaya Alam Dan Lingkungan*, *13*(3), 432–443. https://doi.org/10.29244/jpsl.13.3.432-443

Fantilli, A. P., & Chiaia, B. (2013). The work of fracture in the eco-mechanical performances of structural concrete. *Journal of Advanced Concrete Technology*, *11*(10), 282–290. https://doi.org/10.3151/jact.11.282

Habert, G., Miller, S. A., John, V. M., Provis, J. L., Favier, A., Horvath, A., & Scrivener, K. L. (2020). Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nature Reviews Earth & Environment*, *1*(11), 559–573. https://doi.org/10.1038/s43017-020-0093-3

Lai, F., Zhou, J., Lu, L., Hasanuzzaman, M., & Yuan, Y. (2023). Green building technologies in Southeast Asia: A review. *Sustainable Energy Technologies and Assessments*, *55*, 102946. https://doi.org/10.1016/J.SETA.2022.102946

Langga Chandra Galuh, D., Afif Shulhan, M., & Yasin, I. (2022). LOW CARBON CONCRETE: CEMENT REPLACEMENT UTILIZING FLY ASH. *JOURNAL OF GREEN SCIENCE AND TECHNOLOGY*, *VI*(1).

Lee, J., Lee, T., Jeong, J., & Jeong, J. (2020). Engineering, durability, and sustainability properties analysis of high-volume, PCC ash-based concrete. *Sustainability (Switzerland)*, *12*(9). https://doi.org/10.3390/SU12093520

Lovecchio, N., Shaikh, F., Rosano, M., Ceravolo, R., & Biswas, W. (2020). Environmental assessment of supplementary cementitious materials and engineered nanomaterials concrete. *AIMS Environmental Science*, *7*(1), 13–30. https://doi.org/10.3934/environsci.2020002

Maddalena, R., Roberts, J. J., & Hamilton, A. (2018). Can Portland cement be replaced by low-carbon alternative materials? A study on the thermal properties and carbon emissions of innovative cements. *Journal of Cleaner Production*, *186*, 933–942. https://doi.org/10.1016/j.jclepro.2018.02.138

Maguesvari, U. (2017). Influence of Fly Ash and Fine Aggregates on the Characteristics of Pervious Concrete. In *International Journal of Applied Engineering Research* (Vol. 12, Issue 8). http://www.ripublication.com

Malvar, L., & Lenke, L. (2006). Efficiency of fly ash in mitigating alkali-silica reaction based on chemical composition. *ACI Materials Journal*, *103*.

Olagunju, B. D., & Olanrewaju, O. A. (n.d.). *Comparative Analysis of Different Fly Ash Percentage of Pozzolanic Cement*.

Saraswathy, V., & Song, H. (2006). CORROSION PERFORMANCE OF FLY ASH BLENDED CEMENT CONCRETE: A STATE-OF-ART REVIEW. *Corrosion Reviews*, *24*, 122–187. https://api.semanticscholar.org/CorpusID:138308758

Shaikh, F. U. A., Supit, S. W. M., & Sarker, P. K. (2014). A study on the effect of nano silica on compressive strength of high volume fly ash mortars and concretes. *Materials & Design*, *60*, 433–442. https://doi.org/10.1016/J.MATDES.2014.04.025

Sharvini, S. R., Noor, Z. Z., Chong, C. S., Stringer, L. C., & Yusuf, R. O. (2018). Energy consumption trends and their linkages with renewable energy policies in East and Southeast Asian countries: Challenges and opportunities. In *Sustainable Environment Research* (Vol. 28, Issue 6, pp. 257–266). Chinese Institute of Environmental Engineering. https://doi.org/10.1016/j.serj.2018.08.006

Supit, S. W. M., Shaikh, F. U. A., & Sarker, P. K. (2014). Effect of ultrafine fly ash on mechanical properties of high volume fly ash mortar. *Construction and Building Materials*, *51*, 278–286. https://doi.org/10.1016/j.conbuildmat.2013.11.002

Teixeira, E. R., Mateus, R., Camões, A. F., Bragança, L., & Branco, F. G. (2016). Comparative environmental life-cycle analysis of concretes using biomass and coal fly ashes as partial cement replacement material. *Journal of Cleaner Production*, *112*, 2221–2230. https://doi.org/10.1016/j.jclepro.2015.09.124

Xu, G., Liu, J., Qiao, L., & Sun, Y. (2010). Experimental Study on Carbonation and Steel Corrosion of High Volume Fly Ash Concrete. *2010 Asia-Pacific Power and Energy Engineering Conference*, 1–4. https://doi.org/10.1109/APPEEC.2010.5448649

Yu, F., Sun, D., Wang, J., & Hu, M. (2019). Influence of aggregate size on compressive strength of pervious concrete. *Construction and Building Materials*, *209*, 463–475. https://doi.org/10.1016/J.CONBUILDMAT.2019.03.140

Zhong, R., & Wille, K. (2015). Material design and characterization of high performance pervious concrete. *Construction and Building Materials*, *98*, 51–60. https://doi.org/10.1016/j.conbuildmat.2015.08.027