International Journal of Nanoelectronics and Materials
IJNeaM
ISSN 1985-5761 | E-ISSN 2232-1535

Towards Sustainable Concrete: Performance of Eco-Cement with Agricultural and Industrial Waste Materials

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Received 9 September 2025, Revised 9 October 2025, Accepted 27 October 2025

ABSTRACT

The construction industry is a major contributor to global carbon dioxide (CO_2) emissions, largely due to the widespread use of Ordinary Portland Cement (OPC). This study investigates the potential of eco-cement produced by replacing agricultural and industrial waste materials as a sustainable alternative to customary cement. The performance of eco-cement partially replaced by Rice Husk Ash (RHA) (agricultural waste) and waste glass particles (industrial waste) was evaluated in terms of compressive strength, water absorption, porosity, and environmental impact. The results highlighted that the control sample consistently achieved impressive compressive strength up to 21.88 MPa, particularly during the early age of curing. However, the involvement of Supplementary Cementitious Materials (SCMs) demonstrated slightly slow strength gain for most of the curing age. Among the SCMs, OPC/RHA evaluated samples demonstrate the most reliable and remarkable improvement for all assessed criteria, indicating an acceptable durability, followed by OPC/Waste Glass Powder (WGP) and OPC/All samples. For the sustainability assessment, the incorporation of RHA and WGP resulted in a decline in CO_2 emissions, with OPC/WGP presenting a noticeable potential for CO_2 savings of 4.4%. The study reveals that the combination of RHA and WGP in eco-cement is able to develop good compressive strength and minimising the environmental footprint of concrete production. Overall, this study supports the use of eco-cement as a sustainable construction material, offering both performance advantages and a major decrease in environmental impact compared to traditional cement production.

Keywords: *Supplementary cementitious materials, sustainable concrete, rice husk ash, waste glass powder, CO_2 emission reduction*

1. INTRODUCTION

One of the most compelling aspects of eco-cement innovation is the waste-to-resource narrative. Notably, the global cement industry is responsible for approximately 7% to 8% of global CO_2 emissions. It produces approximately 2.8 billion tonnes annually, with most emissions arising from energy-intensive clinker production processes [1], [2]. Agricultural and industrial by-products, such as rice husk ash (RHA), fly ash, slag, and silica fume, have demonstrated significant potential to replace or supplement traditional cement components. These waste materials, once perceived as burdensome waste products, can now be utilised to create high-performance cementitious blends, offering both environmental and economic benefits. In particular, RHA and fly ash have garnered attention for their ability to enhance the physical properties of cement-based materials, such as improving workability, durability, and strength, while also contributing to the reduction of waste in landfills [3], [4]. In essence, the transformation of these by-products into valuable resources plays a vital role in promoting a circular economy in the construction industry.

However, the transition to eco-cement is not without challenges, particularly in ensuring that these materials meet or exceed the performance benchmarks set by traditional cement. In particular, performance evaluation remains a critical aspect in validating the viability of ternary eco-cements, which combine multiple supplementary cementitious materials (SCMs) to optimise the material's properties. Accordingly, research has proven that incorporating agricultural and industrial waste-based SCMs can significantly enhance both the mechanical strength and durability of cementitious materials. This includes improving their thermal stability and resistance to environmental degradation [5], [6]. This study evaluates the performance of a ternary eco-cement blend, examining the synergies between various waste-based materials and their impact on the overall sustainability and effectiveness of the final product.

The effectiveness of SCMs in concrete depends on their physical and chemical properties, which influence the structural buildup and long-term performance of cementitious pastes. At the same time, factors such as particle size, surface potential, and chemical reactivity play a significant role in determining the suitability of SCMs for specific applications. For instance, the use of calcined clays has demonstrated potential due to their ability to enhance the strength and durability of concrete, provided they are processed under optimal conditions. As such, the ongoing research and development in this field aim to optimise the use of SCMs, ensuring that they contribute positively to the performance and sustainability of concrete structures.

In this study, the innovative use of a combination of RHA and WGP as SCMs in eco-cement, offers a sustainable alternative to traditional OPC. The study highlights the dual benefits of improving concrete performance while significantly reducing CO_2 emissions, enhancing environmentally friendly concrete manufacturing.

2. EXPERIMENTAL METHODS

This experimental work consisted of several stages, including the preparation of raw materials, casting, and sample testing.

2.1. Raw Materials

An ordinary Portland cement (OPC) was utilized in all control concrete and mixes, with various replacement levels of SCMs, namely RHA produced from agricultural waste and waste glass powder (WGP) from industrial waste, to form ternary binders. For RHA, it was prepared under controlled burning conditions at 650°C for one hour with a heating rate of 10°C/min, followed by grinding and sieving processes to obtain a 63 µm particle size. A detailed explanation of the effect of burning temperature and the assessment can be viewed in [7]. In these cement replacements, OPC was partially replaced by 5 wt.% RHA and WGP substituted were from 0 to 10 wt.%. Further details regarding the oursourcing, burning process of rice husk, and their properties are outlined in [7]. Meanwhile, WGP was supplied by Nippon Glass Electric (M) Sdn Bhd (NEGM), Selangor, Malaysia. This as-received WGP, known as electrostatic precipitator (EP) dust, originates from the glass industry for abating particles discharged from glass furnaces using electrical energy. According to Figure 1, these charged particles, either positive or negative, are then attracted to collector plates carrying the opposite charge. The collected particles may be removed from the collector plates as dry EP dust. Additionally, this non-beneficial material has contributed to the increment in operating cost since the disposal requires a special procedure by the local authority. Currently, EP dust is not widely adopted in any research fields, and its key performance added as an alternative cement replacement in concrete should be investigated.

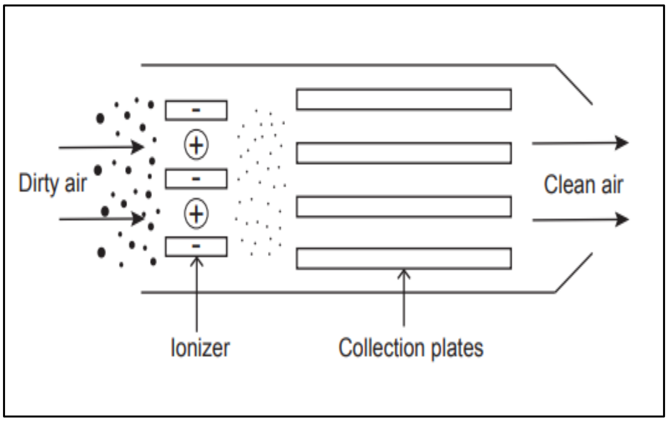

Figure 1. Process on how the EP dust was collected.

This small range of binder replacement was selected to understand the effect of binders used on the overall performance of eco-concrete samples. The physical properties and chemical and mineralogical compositions for all raw materials used in this study are presented in Table 1 using an X-ray Fluorescence (XRF) spectrometer. Correspondingly, the chemical composition of OPC used in the current study disclosed that it has a greater amount of Calcium Oxide (CaO) compared to other typical compositions of OPC from other countries [8], [9], [10]. In addition, EP dust contains a greater amount of Boron Trioxide (B_2O_3), reaching 77 wt.%, followed by Sodium Oxide (Na_2O) and Potassium Oxide (K_2O). Based on the chemical analysis, it is evident that the RHA used can be considered a high-siliceous material due to the sum of total oxides, including Silicone Dioxide (SiO_2), Aluminium Oxide (Al_2O_3), and Iron (III) Oxide (Fe_2O_3), of natural pozzolan being above 70%, which is in good agreement as per ASTM C618 standards.

The particle size distributions of OPC, RHA, and WGP are presented in Figure 2. Each of the materials has a slightly different particle size distribution. The figures also indicate that OPC is coarsely graded compared to RHA and WGP. Moreover, each of the materials is very fine and has particle size distributions that allow it to pass through a 0.5 mm sieve opening. All the materials exhibit a decrease in average particle size as the sieve opening size increases. It is also proven that the particles of RHA are finer than those of OPC, and the finer particles of RHA are well graded in their distributions.

Table 1 Main physical properties and chemical composition of OPC, RHA, and WGP

Parameters (wt.%)	OPC	RHA	WGP
SiO_2	6.39	88.99	0.05
Al_2O_3	1.19	0.05	0.08
Fe_2O_3	4.58	0.12	0.03
CaO	82.9	1.18	0.10
MgO	0.56	0.60	0.09
K_2O	0.88	6.50	10.71
Na_2O	-	0.05	16.32
SO_3	2.66	0.71	-
B_2O_3	-	-	77.00
Other	0.84	1.81	-

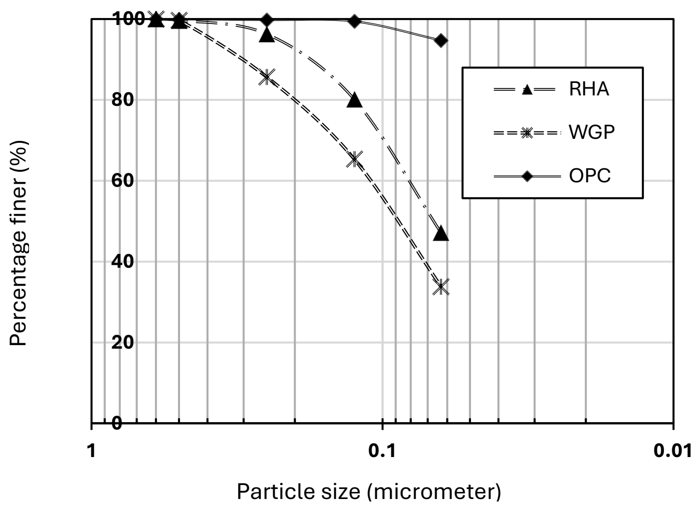

Figure 2. Particle size distribution for all materials used.

The microstructural analysis at higher magnifications can only observe the difference in morphology between RHA and WGP. Evidently, the outer surface of RHA presents a smooth and dense cone-shaped structure that is covered with orderly bumps. Meanwhile, WGP are irregular, angular particles with rough and porous surfaces.

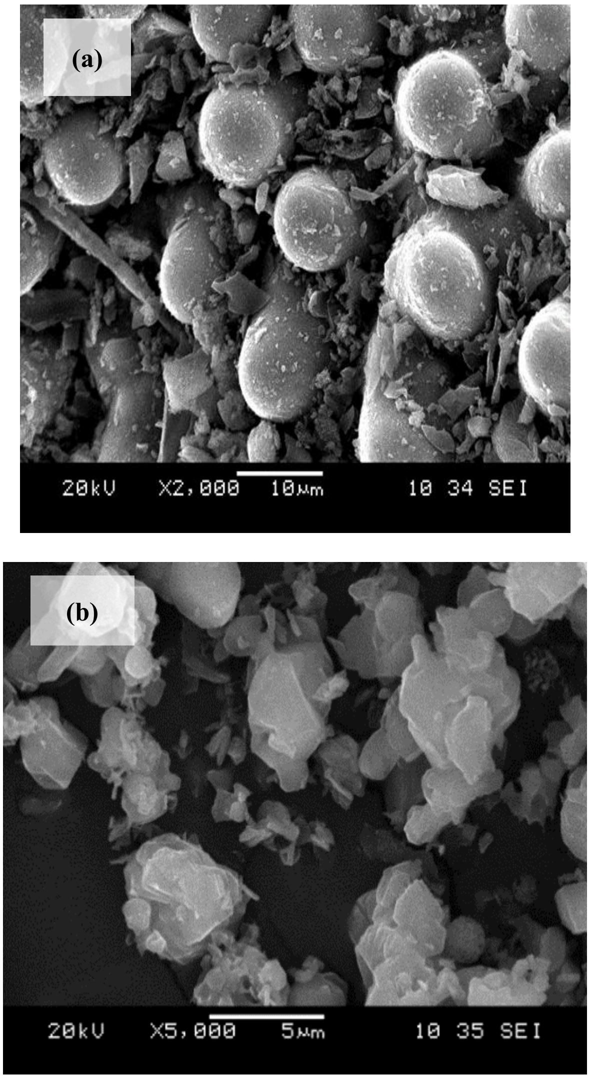

Figure 3. SEM images for (a) RHA and (b) WGP at higher magnification.

2.2 Concrete Mixes and Sample Preparation

All concrete mixes were prepared with a constant water-to-cement (w/c) ratio of 0.4. The details of the mix design for the samples are provided in Table 2. Note that concrete mixes were properly labelled and prepared by hand mixing. For this casting procedure, all dry ingredients were mixed for 1 minute to achieve homogeneity, followed by the addition of aggregates. Superplasticiser (SP) was mixed thoroughly with water and then added gradually to the mixture. The wet mixing was continuous hand mixing for approximately 3 min. After mixing, fresh concrete was poured into various shapes of moulds, i.e., prisms and cubes, depending on the type of testing, to fill approximately one-third of their volume. The concrete was rodded 25 times, and the mould was vibrated using a rubber hammer. This procedure was repeated until the mould was completely filled with concrete. All samples were covered with plastic wrap in a laboratory environment and stored for 24 h. Immediately after completing 24 h, all the samples were demoulded and placed in a water tank until the time of testing. An average of three samples was used at each testing age of the control mix and ternary concrete mixes with RHA and WGP. The mixture IDs are referred to as OPC, OPC/RHA, OPC/WGP, and OPC/All, respectively, and detailed IDs are according to the mixture proportion, as summarised in Table 2. Concurrently, these samples were investigated to understand their mechanical and durability performances as mentioned in the testing procedure section.

Table 2 Mix composition for 1 m^3 of OPC and binary concretes using RHA and WGP at w/c = 0.4

Mixture ID	Mixture Proportion (%)			Constituent materials (kg/m^3)				
	OPC	RHA	WGP	OPC	FA	CA	Water	SP
Control	100	-	-	544	544	1331	170	2
OPC/RHA	95	5	-	517	544	1331	170	2
OPC/WGP	95	-	5	517	544	1331	170	2
OPC/All	90	5	5	490	544	1331	170	2

**FA-Fine aggregate, CA-Coarse aggregate*

2.3 Experimental Procedure

2.3.1 Compressive strength, estimation of compressive strength, and Strength Activity Index (SAI)

The development of compressive strength in different mixture proportions and at various concrete ages, with dimensions of 100 x 100 x 100 mm, was determined by following the procedure outlined in ASTM 513-11. All samples were assessed at the ages of 7, 14, 21, and 28 days. Three samples of each mixture were prepared and evaluated to obtain the average value of compressive strength and the maximum load. Note that the average compressive strength of the three specimens representing each of the strengths of the mixture was calculated using Equation (1). Accordingly, σ represents the compressive strength in MPa, P is the maximum load of the sample in Newton (N), and A is the cross-sectional area of the sample in mm^2:

$$\sigma = \frac{P}{A}. \tag{1}$$

To predict the value of compressive strength at different ages, the fib Model Code 2010 [11], [12], referred to as Equations (2) and (3), has been used for the estimation value.

$$f_{cm}(t) = \beta_{cc}(t).f_{cm}, \tag{2}$$

With

$$\beta_{cc}(t) = exp\left\{s.\left[1-\frac{28}{t}\right]^{0.5}\right\}, \tag{3}$$

where f_{cm} *(t)* is the mean compressive strength of concrete in MPa at an age t in days. Meanwhile, f_{cm} denotes the mean compressive strength of concrete at the age of 28 days, *t* is the concrete age in days, and *s* is a coefficient that depends on the strength class of the cement. In this study, the *s* coefficient value used is 0.38.

The value of the Strength Activity Index (SAI) was determined using Equation (4), where A is the average compressive strength of sample concrete and B is the average compressive strength of control concrete:

$$SAI = \frac{A}{B} \times 100\%. \tag{4}$$

2.3.2 Water absorption

A water absorption test was conducted in this study to calculate the water absorption capacity of hardened concrete following ASTM C-642. The concrete sample, which consists of RHA and WGP, was evaluated after curing in water for 7, 14, 21, and 28 days. Prior to testing, a cube sample measuring 50 × 50 × 50 mm was removed from the curing tank one day in advance. Subsequently, the specimen was wiped to a surface dry condition and weighed to obtain the saturated surface dry weight, W_{sat} of the specimen. Next, the specimen was oven-dried at 105°C for one day, and the oven-dried weight of the specimen was measured. The water absorption of the hardened lightweight concrete was calculated using Equation (5):

$$W = \frac{W_{sat} - W_{dry}}{W_{dry}} \times 100\%, \tag{5}$$

where W is the water absorption of the hardened concrete sample, Wsat is the saturated surface dry weight of the concrete sample, and Wdry is the oven-dried weight of the sample.

2.3.3 Porosity

All samples were dried at 105°C for 2 h and then weighed. The dried samples were placed in the vacuum-saturated machine, evacuated for 2 h, and then soaked in water for 24 h. The samples were wiped with dry clothes and weighed to obtain the saturated surface dry weight. The porosity of the concrete samples was determined using Equation (6):

$$Porosity = \frac{W_{sat} - W_{dry}}{W_{dry}} \times 100\%, \tag{6}$$

where W_{sat} is the saturated dry weight of concrete, and W_{dry} is the oven-dried weight of the sample.

2.3.4 Sustainability assessment of binder mixture

The equivalent CO_2 emissions and CO_2 saving potential for each component were determined according to Equations (7) and (8), respectively [13]:

$$CO_2\ binder = \sum_{i=1}^{n}\left(\frac{m_i}{m_{binder}} \times EF_i\right), \tag{7}$$

where m_i is the mass of material i used in the binder, m_{binder} is the total mass of the binder, EF_i is the emission factor of the material, and n is the number of binder components.

Calculation for CO_2 saving potential:

$$CO_2\ saving\ (\%) = \frac{C_{OPC} - C_{mix}}{C_{OPC}} \times 100, \quad (8)$$

where C_{OPC} is a CO_2 emission of 100% OPC, and C_{mix} is a CO_2 emission of a mixture.

3.RESULTS AND DISCUSSION

Figure 4 presents the evaluation of compressive strength for control sample and the eco-concrete samples between 7 and 28 days of water curing. As expected, the strength for all samples increases with curing time as the concrete continues to harden and gain strength over time. At 21 and 28 days of curing, it becomes apparent that the strength becomes more stable, which is common for cementitious materials. In particular, the control sample dominated consistency of higher compressive strength compared to other samples at most curing ages. However, the replacement of SCMs slightly reduces the strength, especially at the initial stage of curing. For sample OPC/RHA and OPC/WGP, a similar trend of delay in strength development was observed at early curing ages of 7 and 14 days, due to the acceleration of the early hydration process. A similar trend in this activity was found in [14], as SCMs enhance long-term hydration without significantly increasing early strength. Among these samples, the OPC/All demonstrates a balanced performance with acceptable strength values that fall between the control and other binder samples. Thus, it can be considered that while the combination of RHA and WGP benefits the overall hydration, it does not lead to a drastic strength increase. Overall, the compressive strength follows this sequence from highest to lowest: OPC > OPC/RHA > OPC/WGP > OPC/All.

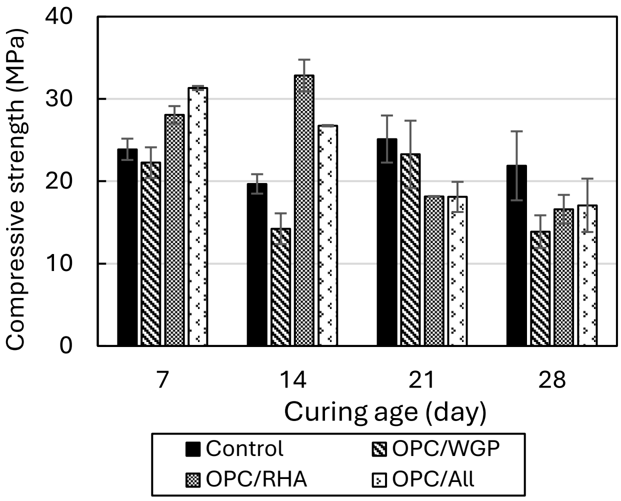

Figure 4. Variation of strength development in samples up to 28 days.

According to the estimation values obtained based on Equations (2) and (3), the model provides reliable trends on compressive strength development. Furthermore, the prediction presents closely matching values at 28 days of curing for all samples (refer to Figure 5). Nonetheless, the estimation values at an early age of curing are lower than the actual values. This can be clearly observed for OPC/RHA and OPC/WGP samples between 7 and 21 days of curing age. Based on this observation, it can be suggested that the model may work well for long-term predictions of compressive strength development exceeding 28 days. By this time, it can be assumed that most of the hydration has completely occurred and that the pozzolanic activity from SCMs has had sufficient time to fully develop its effects.

To better understand the compressive strength behaviors, SAI can be determined, as it is commonly used to evaluate the effectiveness of pozzolanic materials in improving concrete strength, as recommended by ASTM C-311. SAI values greater than 75% are considered satisfactory, indicating that the SCM concrete exhibits sufficient pozzolanic activity and effectively contributes to the concrete strength. Conversely, if the SAI values are less than 75%, the SCM may not adequately react to enhance concrete strength effectively. Based on Figure 6, OPC/RHA is the most effective SCM as it is able to maintain SAI above 75% with a notable improvement after 21 days. The high silica content and fineness of the RHA are believed to contribute to its higher SAI value [15]. Notably, OPC/WGP initially demonstrates a good performance with SAI above 75%. However, its effectiveness diminishes after 14 days. In contrast, OPC/All has not performed well as the SAI values remain below 75% for most curing ages.

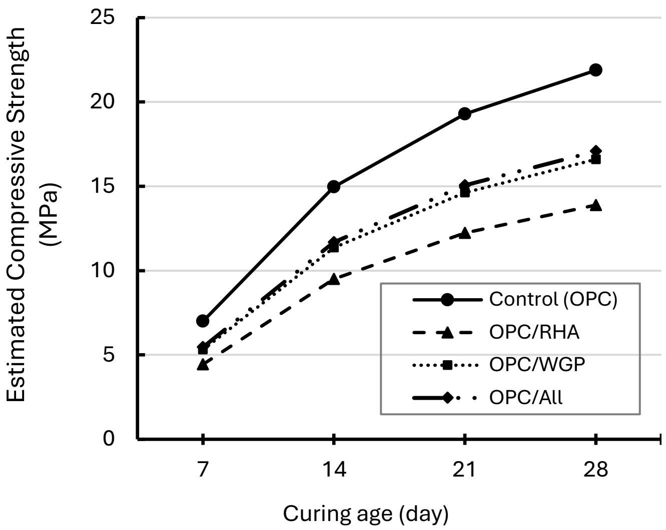

Figure 5. Estimated values of compressive strength for all samples between 7 and 28 days.

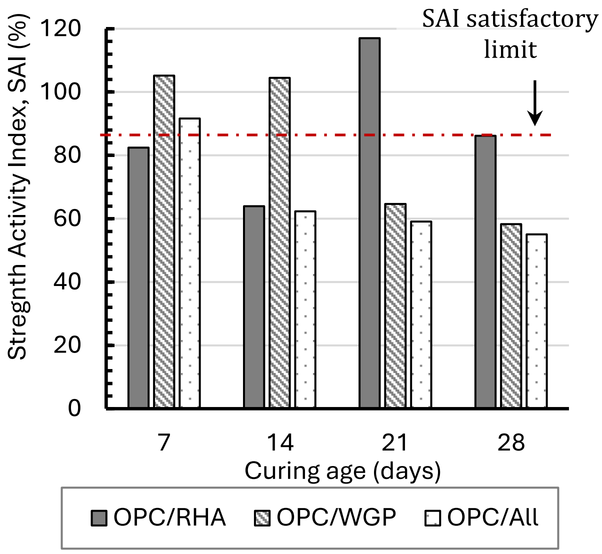

Figure 6. Strength activity index (SAI) for different mixed over curing times.

The water absorption and porosity data provide essential information regarding the durability and performance of concrete samples with the addition of SCMs. By referring to Figure 6, water absorption for all samples decreased as curing progressed, with OPC/RHA demonstrating the most reduction value, from 9.79% to 4.57%. This reveals its effectiveness in improving water resistance. Conversely, OPC/WGP exhibits more irregular behaviour with absorption reaching 8.62% on day 21 before slightly decreasing. The result of porosity also highlighted the similar trends with OPC/RHA, indicating a considerable reduction in porosity from 3.24% to 0.23%. This suggests that RHA is capable of developing denser and more porous structures compared to OPC/WGP and OPC/All, while simultaneously demonstrating an enhancement in porosity, albeit with less consistent results. According to this data, a clear correlation exists between water absorption, porosity, and compressive strength in all tested samples. The OPC/RHA yields impressive outcomes as it is able to improve water resistance and reduce porosity, resulting in acceptable compressive strength, in contrast with OPC/WGP and OPC/All mixes.

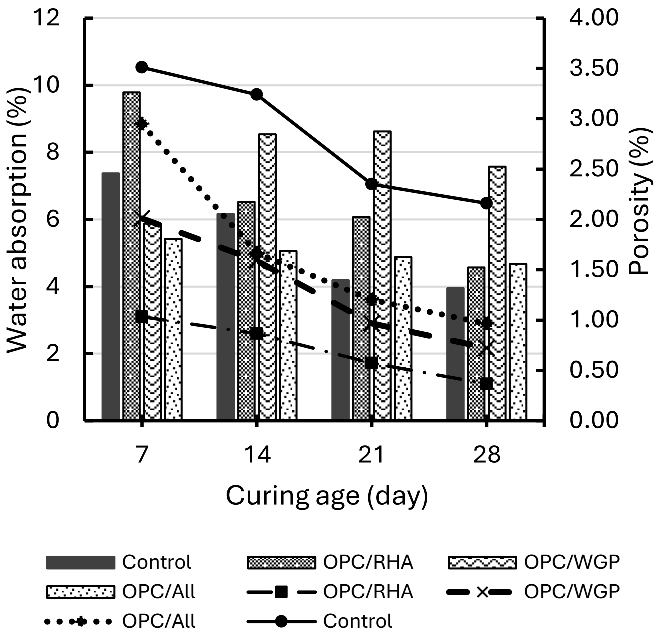

Figure 6. Comparison data on water absorption and porosity for all mixed at different curing times.

By estimation value of CO_2 emission of 0.90 [16], 0.02 [17], and 0.01 [18] kg CO_2/kg binder for OPC, RHA, and WGP, respectively, the amount of CO_2 emission is presented in Table 3. The main target is to achieve lower CO_2 emissions, as this represents a more sustainable mixture that produces less CO_2 per kilogram of material. Correspondingly, samples of OPC/RHA, OPC/WGP, and OPC/All demonstrate a reduction in CO_2 emissions as expected compared to the control sample (pure mixture of OPC), with OPC/WGP indicating the lowest CO_2 emission at 0.8600 kg CO_2/kg binder. Conversely, OPC/WGP highlighted the highest CO_2 saving potential, approaching 4.4%, followed by OPC/RHA at 4.12%. Additionally, OPC/All offers a slightly lower environmental benefit compared to the individual use of RHA or WGP. Additionally, a study by Satihiparan et. al (2024) [19] found that the utilization of 5% of waste has resulted in 18.75% of CO_2 reduction. The differences could be related to variations in experimental conditions, and methodologies. By optimizating the mix design and waste material content could potentially increase the CO_2 reduction values.

Table 3 CO_2 emission and saving potential data

Mixture ID	Estimated CO_2 Emission (kg CO_2/kg binder)	CO_2 Saving Potential vs. OPC (%)
Control	0.9000	0.00
OPC/RHA	0.8629	4.12
OPC/WGP	0.8600	4.44
OPC/All	0.8669	3.68

3. CONCLUSIONS

In conclusion, this study enhanced the impact of SCM's addition on compressive strength, water absorption, and porosity of concrete samples. Specifically, OPC/RHA can be nominated as the best-performing mix among others evaluated. It effectively maintained an acceptable compressive strength of 16.6 MPa at 28 days of curing and a high SAI value of 55.05%, while significantly reducing water absorption and porosity. This indicates that RHA has the capability to advance a denser and more durable concrete structure. In contrast, OPC/WGP exhibited inconsistent performance, whereas OPC/All showed improved water absorption and porosity. However, it had lower and irregular compressive strength. From the sustainability overview, the CO_2 saving potential for OPC/RHA and OPC/WGP of 4.12% and 4.44% , respectively present new opportunities for reducing the environmental footprint in concrete. Nevertheless, the OPC/All mix exhibited the lowest CO_2 saving potential (3.68%), indicating that the combination of RHA and WGP may not be as effective as using them individually. This study underlines the potential of RHA and WGP as sustainable SCMs, contributing to the development of eco-friendly concrete mixtures with improved durability and lower environmental impact, providing valuable insights for future concrete advancements.

ACKNOWLEDGMENTS

We would like to extend our appreciation for the support from the Fundamental Research Grant Scheme (FRGS) under grant number 9003-00748: FRGS/1/2019/TK06/UNIMAP/02/6 from the Ministry of Higher Education (MoHE), Malaysia, and grant number 600-RMC/MyRA 5/3/LESTARI (053/2020).

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