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Mechanical Properties of Eco-friendly Alkali-activated Concrete Containing Plastic Waste and Crumb Rubber Tires

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Abstract

This study aims to investigate an eco-friendly concrete for sustainable development in construction materials. Alkali-activated concrete was produced using by-product wastes, *i.e.*, fly ash and rice husk ash. Crumb rubber obtained from waste tires was used as fine aggregate. Crushed plastic automotive parts were used to replace natural limestone at replacement levels of 10% and 20% by volume. The results showed that adding crumb rubber and plastic waste up to 20% reduced the unit weight and slump of alkali-activated concrete, while increasing its strain capacity under compression. The 28-day compressive strength of rubberized concrete containing plastic waste ranged between 5.4 and 10.0 MPa, suggesting its suitability for use as a subbase beneath slabs or pavements. In addition, based on the mechanical performance, environmental sustainability, and cost-efficiency discussed in this study, incorporating 10% crumb rubber or 10% plastic waste is considered the optimal replacement level in concrete mixtures.

Keywords: Alkali-activated concrete; Crumb rubber; Plastic waste; Rubberized concrete; Mechanical properties; Recycled aggregate.
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1. Introduction

Concrete is considered to be an indispensable material in construction industry today due to its excellent resistance to water, good performance in compression, low cost, and long service life.[1–3] In addition to aggregates (usually sand and crushed stone), the concrete is mainly comprised of water and Portland cement acting as a binder to bind the aggregate particles together to form a rocklike mass. Although these materials are readily available in many regions around the world, the production of Portland cement clinker is one of the most CO_2-intensive sectors, generating approximately 843 kg of CO_2 per ton of clinker.[4] This accounted for approximately 7% of global annual emissions, making a significant contribution to environmental issues.[5–7] Moreover, mining of sand from riverbeds or quarries and the production of crushed limestone (*i.e.*, extraction, hauling and crushing processes) are a global environmental concern.[8,9] Therefore, the use of alternative materials for manufacturing sustainable concrete is needed to reduce CO_2 emission and preserve natural resources.

Alkali-activated cement is one of the binding mediums known as an eco-friendly alternative to ordinary Portland cement. The average CO_2 emissions of concrete made from the cement is approximately 40%-65% lower than that of Portland cement concrete.[10,11] Various industrial and agricultural wastes such as slag, fly ash, rice husk ash, and sugarcane bagasse ash have been successfully used as precursors for producing alkali-activated cement.[12–14] Its cementitious slurry can be achieved by adding these materials to hydroxide-, silicate- or alkaline carbonate solutions.[15] In addition, water is sometimes added to achieve the target workability and to enhance intermediate reactions during gel formation, such as dissolution and hydrolysis.[16] When the slurry hardens into a strong mass, it demonstrates strength and durability, which are the desirable engineering characteristics of concrete, which are the desirable engineering characteristics of concrete, leading to the application of practical scenarios.[17]

In addition to cementitious materials, aggregates account for more than 60% of the total constituents in concrete production. Aggregates function primarily as inert fillers and significantly influence the dimensional stability of hardened concrete. Conventionally, they are sourced from natural mineral deposits, including carbonate rocks, gravel, granite,

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Table 1: Chemical compositions (% by weight) and physical properties of high calcium fly ash and RHA.

Materials	SiO_2	Al_2O_3	CaO	Fe_2O_3	SO_3	MgO	Na_2O	K_2O	Specific gravity	LOI (%)	Surface area(m^2/g)
Fly ash	31.5	16.0	25.2	12.4	3.6	2.4	2.6	2.0	2.5	0.3	3.5
RHA	88.7	-	0.8	0.9	-	0.4	0.1	2.0	2.2	2.0	17.1

basalt, and sand. However, increasing concern over the depletion of natural resources has led to growing interest in the utilization of alternative materials, such as crumb rubber and plastic waste, as aggregate substitutes in concrete. Both crumb rubber and plastic waste are generated in large quantities and are often improperly disposed of, contributing to significant environmental concerns.[18,19] One effective approach to mitigate this issue is their reuse or recycling in the production of construction materials, particularly concrete.[20]

Rubber waste is being generated at an accelerating rate in parallel with the increasing production of vehicle tires, driven by population growth and the expansion of transportation systems. It is estimated that approximately 1.2 billion tires will be discarded annually worldwide by 2030,[21] leading to various environmental problems. Various disposal methods for tire waste—such as recycling, re-treading, landfilling, and energy recovery—have been proposed. However, among these, landfilling is considered the least effective and most environmentally detrimental option. The disposal of tires in landfills poses significant environmental concerns, including the potential leaching of hazardous and toxic substances into the surrounding ecosystem.[22] One feasible approach for the reutilization of waste rubber tires is converting them into crumb rubber and incorporating it as aggregate in concrete production. The utilization of crumb rubber in Portland cement concrete was reported by Meyyappan *et al*.[23] who concluded that a 10% replacement level was optimal, yielding performance comparable to mixtures incorporating natural sand. Wang *et al*.[24] reported that the optimal replacement level of crumb rubber as fine aggregate in alkali-activated concrete ranged from 10% to 15%, which provided an acceptable reduction in mechanical properties. Moreover, several studies[25,26] have reported that the increase of crumb rubber replacement levels resulted in the drastic reduction of mechanical properties.

Plastics are extensively used across various sectors, including daily life and industrial applications, due to their low density, ease of processing, and moldability.[27] Nevertheless, the escalation of plastic consumption leads to the dramatic amount of plastic waste in the environment, leading to several environmental issues. Currently, approximately 300 million tons of plastic waste are generated globally on an annual basis.[18] Furthermore, the disposal of plastic waste through non-environmentally friendly methods contributes significantly to environmental pollution and poses risks to human health.[28] The reuse of plastic waste in the construction sector represents a promising and sustainable approach for managing plastic waste.[29] Previous findings[30–33] have reported that the utilization of plastic waste as aggregates in cementitious materials contributed to reduce utilizing natural aggregates, leading to the reduction of CO_2 emission. Also, it provided the feasibility approach the application of plastic waste in construction materials. However, the increase of plastic waste replacement levels resulted in the adverse effect of mechanical properties in composites. Oddo *et al*.[34] who investigated the incorporation of plastic waste into Portland cement concrete, reported that using plastic waste at levels up to 20% had only a minor impact on the mechanical properties. Haruna *et al*.[35] reported incorporating plastic waste at a 10% replacement level in alkali-activated concrete is optimal, yielding mechanical properties comparable to mixtures with natural aggregates. Although higher plastic content led to a reduction in mechanical performance, it contributed to a decrease in the overall embodied CO_2 emissions.

Despite extensive research on the incorporation of crumb rubber and plastic waste in conventional concrete, their application in alkali-activated concrete remains limited—particularly when plastic waste is added to rubberized concrete. The objective of this study is to investigate the workability and mechanical properties of alkali-activated concrete utilizing crumb rubber and plastic waste as aggregates. In addition, the environmental impact and cost-effectiveness were also evaluated.

2. Materials
2.1 Binders
2.1.1 High calcium fly ash
High calcium fly ash was used as a solid precursor in alkali-activated cement. The fly ash was obtained from lignite coal combustion at the Mae Moh power plant in Thailand. As can be seen in Fig. 1 (a), the Scanning Electron Microscopy (SEM) image showed that the morphology of the fly ash particles is spherical. The Chemical compositions and physical characteristics of the fly ash were illustrated in Table 1. The

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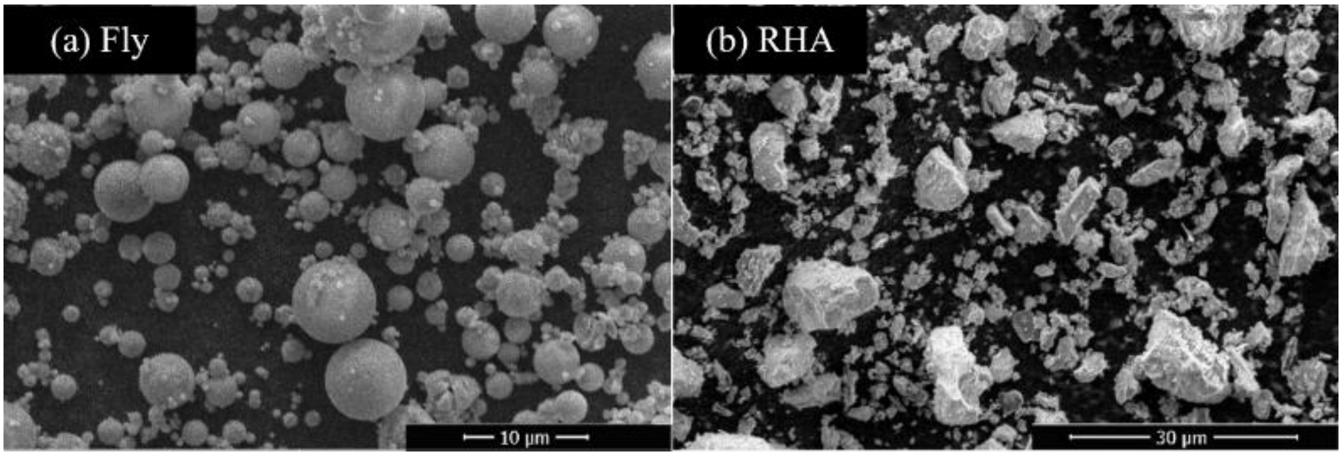

Fig. 1: SEM images of fly ash and RHA used for making alkali-activated concrete.

high calcium fly ash was an aluminosilicate precursor rich in SiO_2 and Al_2O_3, but it consisted of 25.2% CaO.

2.1.2 Rice husk ash

Rice husk ash (RHA) was collected from a clay brick factory in Maha Sarakham, Thailand, where the rice husk was burned for heating purposes. A 45-mesh sieve was used to separate an incompletely burned RHA. After sieving, the RHA was ground in a ball mill for 8 h to obtain the fineness of 17.1 m^2/g. The fine particles react more quickly with mixing liquids, providing a better alkaline activation. The micrograph of RHA showed that the morphology of the RHA was irregular in shape (Fig. 1(b)). Its main chemical component is SiO_2, comprising 88.7% of the total composition (see Table 1).

2.2 Mixing liquids

A sodium hydroxide solution (NaOH) was used as an alkaline activator. It is one of the most activators commonly used to dissolve chemical compounds from precursors. Sodium hydroxide pellets with a purity of 98% were used to prepare the alkaline solution at a concentration of 10 M. In the current study, tap water was also used in alkaline activation, which was successfully used to produce alkali-activated concrete.[36,37]

2.3 Aggregates

2.3.1 Coarse aggregates

A well-graded natural crushed limestone was used as coarse aggregate. Gradation curves of coarse aggregates are illustrated in Fig. 2. The limestone had a maximum size of 19 mm and a specific gravity of 2.67. The dry-rodded unit weight, water absorption, fineness modulus, and Los Angeles abrasion loss of the limestone are illustrated in Table 2. Another type of coarse aggregate used in the current study is wastes from recycled polypropylene plastic. The plastic waste obtained from automotive parts was crushed using a mechanical crushing machine. The natural limestone was replaced with plastic waste at levels of 10% and 20% by volume to maintain the distribution of particle sizes recommended by ASTM C33.[38] The properties of the plastic waste are also shown in Table 2.

2.3.2 Fine aggregates

Two types of materials were used as fine aggregate to produce the alkali-activated concrete: (1) natural river sand and (2) crumb rubber ties. Steel wire meshes were removed from the waste vehicle ties. Then, the waste tire was ground into small grains using a grinding machine before being used as fine aggregate. The characteristics of river sand and crumb rubber are also presented in Table 2. As shown in Fig. 3, the gradation of fine aggregate suitable for preparing concrete can be obtained when the crumb rubber was used at 0%, 10%, and 20% by volume of natural sand.

3. Mixing and preparation of specimen

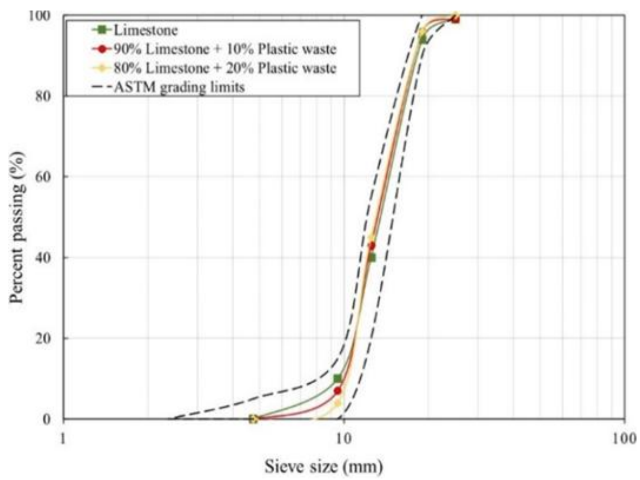

Fig. 2: Gradation curves of coarse aggregates.

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Table 2: Properties of coarse and fine aggregates.

Properties	Coarse aggregates		Fine aggregates	
	Limestone	Plastic waste	River sand	Crumb rubber
Specific gravity	2.7	0.9	2.6	0.6
Dry-rodded unit weight (kg/m^3)	1,650	455	1,672	573
Water absorption (%)	0.6	-	0.8%	-
Fineness modulus	7.21	5.21	3.03	2.73
Los Angeles abrasion loss (%)	31	-	-	-

3.1 Mix proportions

Table 3 shows mix proportions of alkali-activated concrete mixtures used in this study. The concrete can be divided into three categories: concrete with crumb rubber, concrete made from plastic waste, and rubberized concrete containing plastic waste. The abbreviations "10R" and "20R" stand for concretes made with 10% and 20% crumb rubber, respectively. On the other hand, the alkali-activated concretes containing 10% and 20% plastic waste were abbreviated as 10P and 20P, respectively. All concrete mixtures were designed to achieve the water to gel ratio of 0.36. Molar ratios of $Na_2O/SiO_2 = 0.22$, $SiO_2/Al_2O_3 = 4.5$, $H_2O/Na_2O = 16.2$, and $Na_2O/Al_2O_3 = 0.99$ were obtained, which meet the criteria suggested by Davidovits.[39]

3.2 Casting of concrete specimen

Four steps were used to prepare alkali-activated concrete. The high calcium fly ash and RHA were first dry mixed by hand to achieve a uniform binder. Second, the slurry was obtained by mixing the binder with the NaOH solution in a laboratory pan mixer for 3 min. Then, coarse and fine aggregates were added to the mixer, and the mixing process continued for 3 min. Finally, tap water was added and mixing was continued for another 3 min. The fresh concrete was compacted into steel molds by hand-rodding in accordance with ASTM C192.[40] Demolding was done 24 h after casting, and the specimens were then cured in air at a temperature of 28±3 °C.

4. Testing of concrete

4.1 Slump and dry unit weight

Table 4 presents the dimensions of the specimen, and the standard test methods used to evaluate properties of alkali-activated concrete. The flowability of fresh concrete was measured by the slump-cone test according to ASTM C143,[41] while the dry unit weight of concrete was done as per the ASTM C642.[42] The reported values were obtained from three replications.

4.2 Compressive strength and modulus of elasticity

The compressive strength of alkali-activated concrete was determined at the ages of 7-, 28-, and 90-days using cylindrical specimens with a diameter of 10 cm and a height of 20 cm. The cylinders were also cast and used to assess the stress-

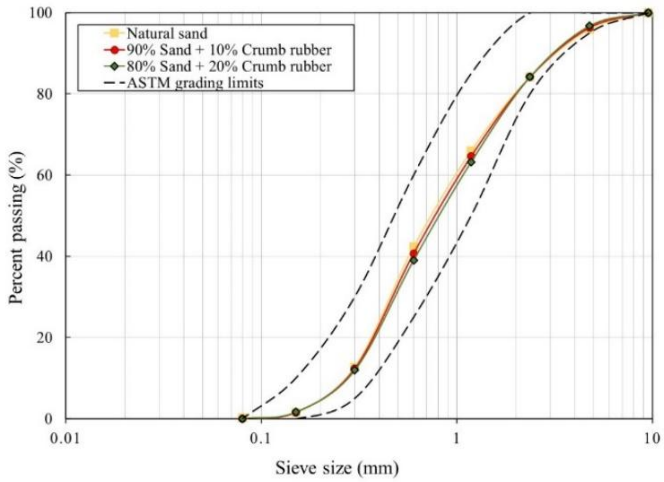

Fig. 3: Gradation curves of fine aggregates used in the investigation.

Table 3: Mix proportions of concrete (kg/m^3).

	Binders		Mixing liquids		Fine aggregates		Coarse aggregates	
Mix	Fly ash	RHA	NaOH	Water	River sand	Crumb rubber	Limestone	Plastic waste
CON	450	54	135	101	500	0	1150	0
10R	450	54	135	101	450	12	1150	0
20R	450	54	135	101	400	25	1150	0
10P	450	54	135	101	500	0	1035	39
20P	450	54	135	101	500	0	920	78
10R-10P	450	54	135	101	450	12	1035	39
20R-10P	450	54	135	101	400	25	1035	39
10R-20P	450	54	135	101	450	12	920	78
20R-20P	450	54	135	101	400	25	920	78

Table 4: Testing of alkali-activated concrete.

Properties	Shape and dimension	Standards	Replications
Slump	-	ASTM C143[41]	3
Dry unit weight	10 cm- Cube	ASTM C642[42]	3
Compressive strength	Ø 10×20 cm- cylinder	ASTM C39[44]	3
Modulus of elasticity	Ø 10×20 cm- cylinder	ASTM C469[45]	3
Flexural strength and toughness	10×10×35 cm-beam	ASTM C1609[43]	3

strain relationship in concrete and modulus of elasticity (Young's modulus) after curing for 28 days.

4.3 Flexural strength and toughness

Three beam specimens of size 10 cm×10 cm×35 cm were prepared for testing of flexural strength and toughness. After the specimens were cured for 28 days, the test was performed as per ASTM C1609.[43] The 20-mm Linear Variable Differential Transformer (LVDT) sensors were used to measure the deflection of the specimen under tensile loading, as shown in Fig. 4.

5. Results and discussions

5.1 Slump and dry unit weight

The results of the slump tests and dry unit weight are presented in Fig. 5 and Fig. 6. Both slump and dry unit weight values decreased with recycled aggregates due to the lightweight nature of plastic waste and crumb rubber. For example, the slump of 20P and 20R concretes decreased by 17% and 10%, respectively, compared to the normal concrete (CON). This is mainly because the slump of concrete occurs under the self-weight of the tested concrete. However, it was noticed that the slump of rubberized concretes containing plastic waste was about one-half of the value obtained from the CON mixture.

Similar to previous studies,[24,46] the dry unit weight of alkali-activated concretes with plastic waste and crumb rubber was lower than that of the reference concrete, mainly because the lower unit weight of recycled aggregates as compared to natural aggregates (Table 2). For example, the dry unit weight of 20R-20P mixture was 1,806 kg/m^3, which was 81% of the CON mixture. However, the results in Fig. 6 indicated that the reduction in dry unit weight remained small when the total content of recycled aggregates did not exceed 10%.

5.2 Compressive behavior of alkali-activated concrete

5.2.1 Stress-strain curves

The influence of crumb rubber and plastic waste on stress-strain behavior of alkali-activated concrete under compression are presented in Fig. 7 and Fig. 8. It can be seen from Fig. 7 (a) that the curve of the CON mixture ended abruptly at the peak, indicating that the mixture is brittle. Similar to the control concrete, the stress-strain curve of concretes made with crumb rubber shows a linear-elastic behavior at early stages. However, the curves for the 10R and 20R mixtures showed a gradual increase in curvature until the specimen fractured. This implies that the development of bond microcracks at the interfaces between the matrix and the aggregate started earlier when crumb rubber was used.

There was a notable difference between the stress-strain relationships of the alkali-activated concrete made with natural aggregate and those with recycled aggregate from plastic waste. As shown in Fig. 7 (b), the slope of the ascending branch decreased appreciably with an increase in plastic waste, mainly because the strain increased at a faster

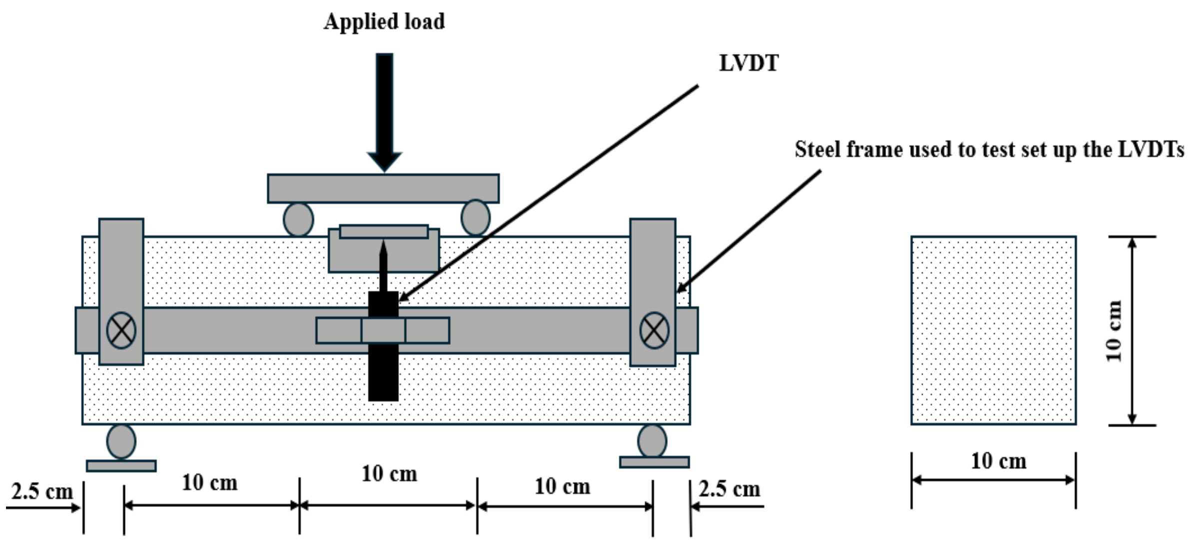

Fig. 4: Test set-up for of flexural strength.

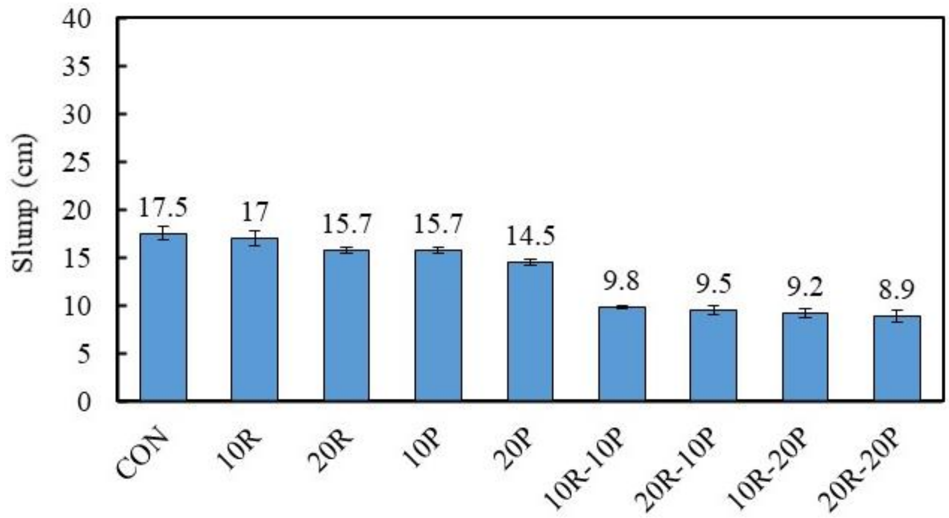

Fig. 5: Slump of alkali-activated concrete.

rate than the applied stress. This indicated that the cracks propagated rapidly in concrete made with plastic waste, especially in the concrete containing 20% plastic waste (20P mixture).

Incorporating plastic waste decreased the initial slope of the stress-strain curve of rubberized concrete but increased the strain capacity of rubberized concrete, as can be seen in Fig. 8. In other words, the use of plastic waste resulted in a more ductile failure with an apparent pseudo-plastic behavior prior to complete fracture. The results also showed that the curve of 20R-20P mixture was long and almost flat at the top, indicating that the interfaces between the mortar and the plastic waste were very weak.

5.2.2 Modulus of elasticity

The variation of the modulus of elasticity of alkali-activated concrete as a function of the crumb rubber content is illustrated in Fig. 9. The elastic modulus at 28 days of the CON mixture was 14.4 GPa, while the values of the 10R and 20R mixtures were 13.7 and 7.8 GPa, respectively, which were approximately 5% and 45% lower than that of the CON mixture. In addition to the low stiffness of rubber, the poor bond between the crumb rubber and the matrix resulted in less stress transfer between them, leading to a lower elastic modulus.[47]The influence of plastic waste on elastic modulus of alkali-activated concrete is also presented in Fig. 9. It can be seen that the values decrease with increasing the content of plastic waste. Compared to the control concrete, the elastic modulus of the 10P and 20P mixtures decreased by 8% and 65%, respectively. The primary reason behind this is that the strength of the interface zone is aggravated due to the addition of smooth texture plastic aggregates.

The elastic modulus at 28 days of rubberized concretes containing plastic waste ranged between 1.5 and 4.0 GPa. It was noticed that the modulus of elasticity for rubberized concretes decreased with increasing in plastic waste content. This behavior was similar to that observed in specimens from both the 10P and 20P mixtures.

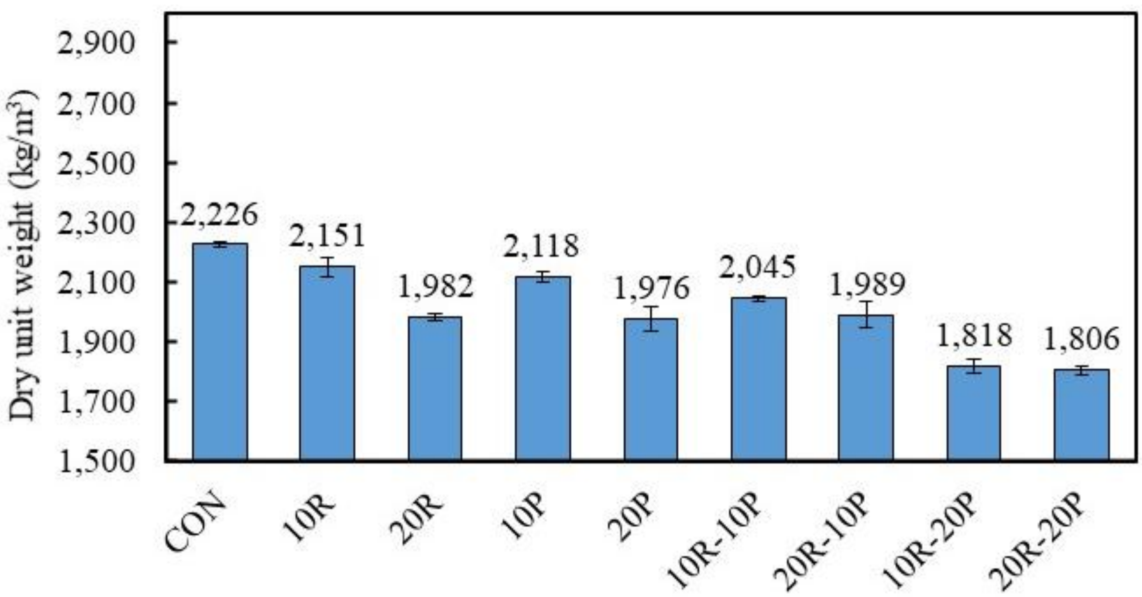

Fig. 6: Effect of crumb rubber and plastic waste on dry unit weight of alkali-activated concrete.

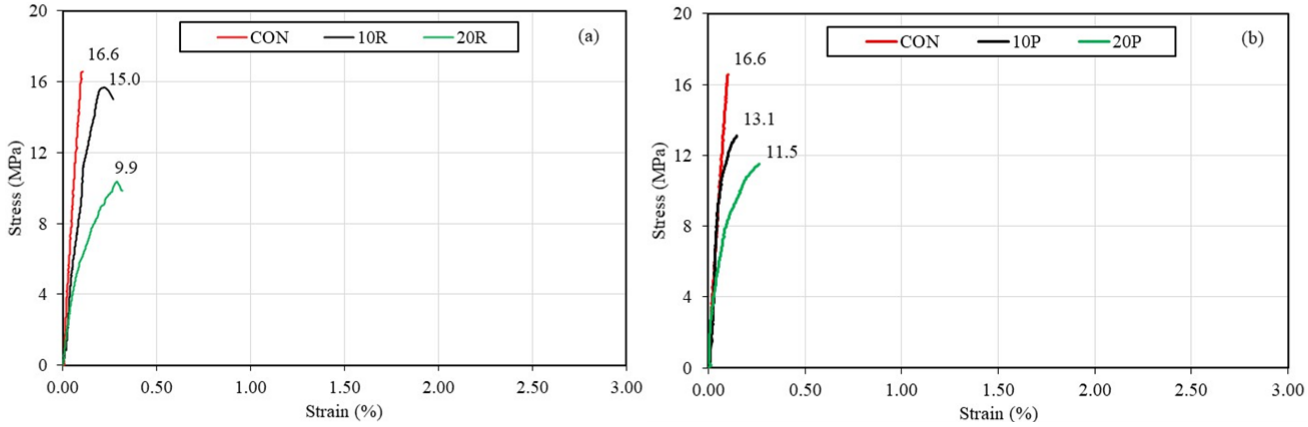

Fig. 7: Influence of crumb rubber and plastic waste on the modulus of elasticity.

5.2.3 Compressive strength

The values of compressive strength for alkali-activated concrete tested are shown in Fig. 10. Similar to the CON mixture, the compressive strength of alkali-activated concrete containing recycled aggregates increased with time. For example, the strength values of 10R-10P mixture were 4.7, 10.0 and 13.2 MPa at 7, 28 and 90 days, respectively. This is mainly attributed to the development of calcium-based gel phases in alkali-activated paste obtained from high calcium fly ash.[48]

As shown in Fig. 10, the decrease in compressive strength at each curing age was observed when the crumb rubber was added. For example, the 28-day compressive strength decreased from 18.9 MPa for the CON mixture to 14.6 MPa and 13.2 MPa for the 10R and 20R concretes, respectively. The low stiffness of the crumb rubber may cause premature cracking in the surrounding cement paste.[49] The finding results are consistent with those of Wang *et al*.[24] and Pradhan *et al*.[50]

The use of plastic waste as coarse aggregate resulted in a reduction of compressive strength in both normal and rubberized concretes. Moreover, it was noticed that the effect was more pronounced in rubberized concrete, which had lower compressive strength compared to the normal concrete (CON). The internal bleed water is mostly located in the vicinity of the plastic particles with non-absorption properties.[51,52] Thus, the interfaces between the mortar and plastic aggregate are easily prone to microcracking.

The strengths of 10R-20P and 20R-20P concretes meet the requirements for controlled low strength materials (CLSM), with compressive strength not exceeding 8.3 MPa. These concretes can be used as structural fill to support loads from foundations in areas with low soil bearing capacity.

5.3 Flexural strength

The measured 28-day flexural strength of alkali-activated concrete is presented in Fig. 11. It was observed that the flexural strength decreased with increasing the content of crumb rubber in concrete, aligning with the variation observed in the compressive strength. However, it was noticed that, compared to the compressive strength, the flexural strength of concrete made with recycled aggregates dropped significantly as the content of crumb rubber increased. Fig. 11 also illustrates the effect of plastic waste on flexural strength of alkali-activated concrete. The results showed that the flexural strength of the 10P and 20P concretes decreased by 32% and 52%, respectively, compared to the control mix. Similar to the compressive strength discussed earlier, the decrease in flexural strength also occurred due to the formation of cracks, which have developed as a result of poor bonding between the plastic particles and the mortar.

It can be seen that the rubberized concretes almost lost their

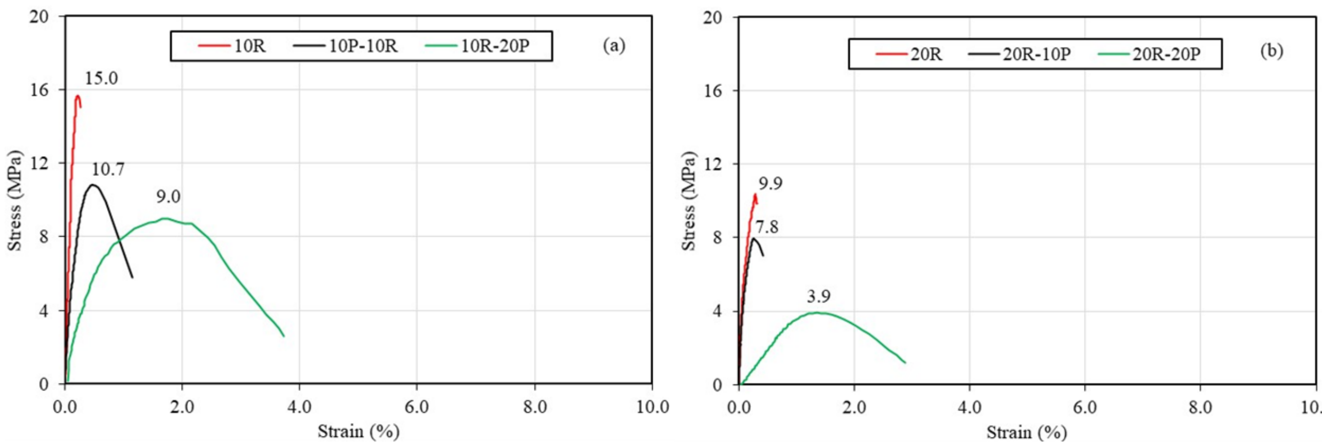

Fig. 8: Stress-stain curves of rubberized concrete containing plastic waste.

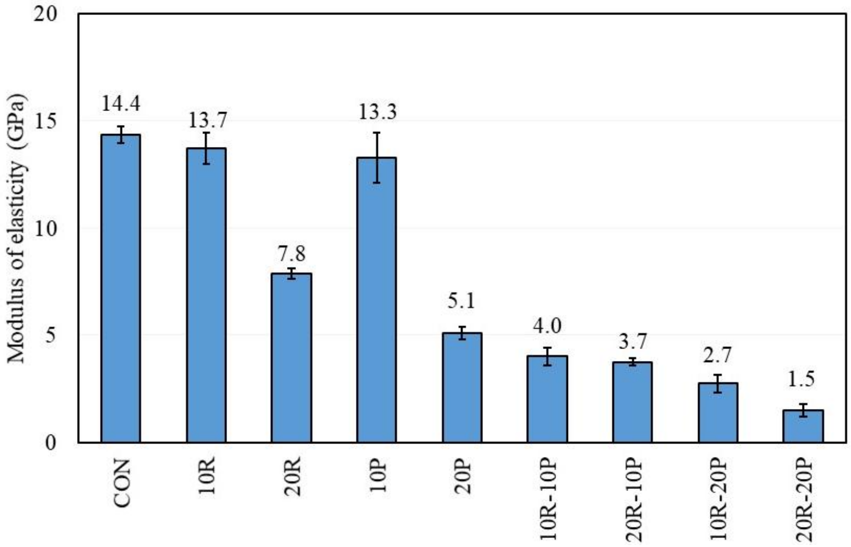

Fig. 9: Modulus of elasticity of alkali-activated concrete.

ability to withstand tensile stress when plastic waste was added. A flexural strength below 1.0 MPa was obtained for the rubberized concretes in which the amount of plastic waste was from 10% to 20%. However, Adnan and Dawood[53] found the use of plastic waste up to 2.5% resulted in an increase in the flexural strength of Portland cement concrete.

5.4 Environmental impact and Cost-effectiveness analysis

The growth of construction activities has resulted in increased cement consumption, thereby contributing significantly to CO_2 emissions associated with cement production in the industry.[54] To mitigate the environmental impact associated with CO_2 emissions from cement production, alkali-activated concrete (AAC) has emerged as a promising alternative material for the development of eco-friendly construction materials. Its effectiveness in reducing environmental impact and enhancing cost-efficiency has been confirmed by previous studies.[55,56] To evaluate the environmental impact and cost-effectiveness of AAC, the total embodied CO_2 emissions (TCE), calculated using Eq. (1),[57] were used to assess its environmental performance. Simultaneously, the cost-effectiveness was evaluated by determining the total production cost, calculated using Eq. (2).[57] The embodied CO_2 emissions factor and cost of materials are presented in Table 5.

$$\text{The total embodied } CO_2 \text{ emissions } (kg \cdot CO_{2-e}/m^3) = \sum_{i=1}^{n} QM \times ECF \quad (1)$$

$$\text{The total production cost } (USD/m^3) = \sum_{i=1}^{n} QM \times CM \quad (2)$$

where the QM is the quantity of materials (kg/m^3), ECF is the embodied CO_2 emission factor of materials (kg·$CO_{2\text{-}e}$/kg), and CM is the cost of materials (USD/ton)

Fig. 12 illustrates the total embodied CO_2 emissions (TCE) of AAC incorporating crumb rubber and plastic waste. As shown in the control mixture (CON), the TCE was 227.3 kg·$CO_{2\text{-}e}$/m^3, representing a reduction of approximately 29% and 36% compared to the results reported by Turner and Collins[70] for Portland cement concrete and geopolymer

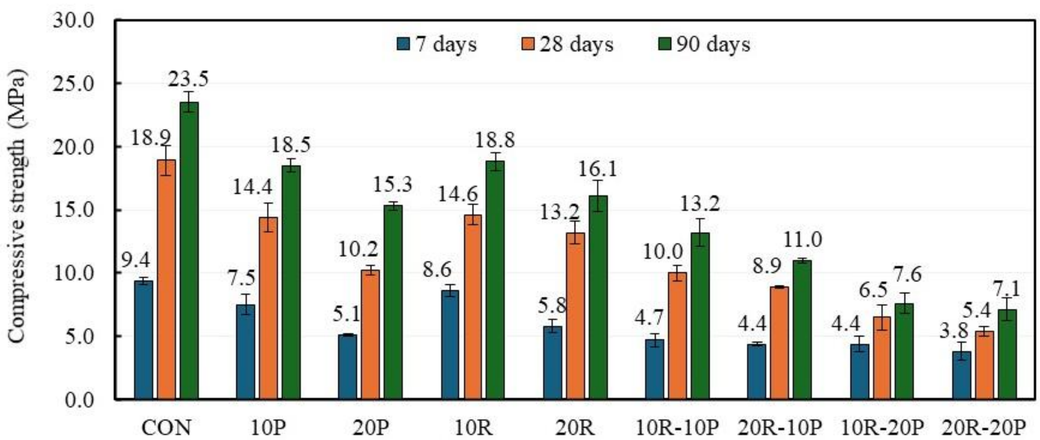

Fig. 10: Compressive Strength of alkali-activated concrete at 7, 28, and 90 days.

Table 5: Embodied CO_2 emissions and cost of AAC materials.

Material	Equivalent CO_2 emission (kg·CO_{2-e}/kg)	Unit price (USD/ton)
Fly ash	0.009[57,58]	17.6[59]
RHA	0.103[60]	15[61]
NaOH	1.246[62]	273[63]
Water	0[64]	2.1[65]
River Sand	0.00471[54,66]	13.2[59]
Crumb Rubber	3.142[67]	265[68]
Limestone	0.041[58]	16.2[59]
Plastic	-0.509[54,69]	200[54]

concrete, respectively. In mixtures incorporating plastic, the TCE exhibited a decreasing trend with increasing levels of plastic replacement in AAC. Specifically, the TCE values for mixtures 10P and 20P were 202.8 and 178.2 kg·CO_{2-e}/m^3, reflecting reductions of approximately 11% and 22%, respectively, compared to the CON mixture. Meanwhile, it is noticeable that the mixture incorporating crumb rubber showed a significant reduction of TCE when the crumb rubber replacement level increased. The TCE values for mixtures 10R and 20R were 189.4 and 148.3 kg·CO_{2-e}/m^3, representing reductions of approximately 17% and 35%, respectively, compared to the CON mixture. These results demonstrate that the incorporation of plastic or crumb rubber in AAC led to a reduction in TCE, indicating significantly lower CO_2 emissions and enhanced environmental sustainability, which is consistent with previous findings.[54,67] Interestingly, the utilization of plastic and crumb rubber as a replacement aggregate in AAC is attributed to the drastic reduction of TCE, as presented in Fig. 12. For the mixtures 10R-10P, 20R-10P, 10R-20P, and 20R-20P, the TCE values were 164.8, 123.7, 140.3, and 99.2 kg·CO_{2-e}/m^3, representing approximate reductions of 28%, 46%, 38%, and 56%, respectively, compared to the CON mixture. These findings clearly indicate that the incorporation of both plastic and crumb rubber into AAC can effectively reduce TCE, contributing to the development of more environmentally friendly construction materials. This approach offers a viable alternative for utilizing recycled waste in the production of sustainable construction materials.

The total production cost of AAC mixtures is presented in Fig. 13. The production cost of CON mixture was 71.0 USD/m^3. Compared to the CON mixture, the replacement of sand with plastic or crumb rubber resulted in an increase in production cost by approximately 8.4%, 16.7%, 3.5%, and 7.5% for the 10P, 20P, 10R, and 20R mixtures, respectively Moreover, AAC mixtures incorporating both plastic and crumb rubber as replacement aggregates resulted in a notable increase in production cost by approximately 11.9%, 15.8%, 20.3%, and 24.2%, respectively, compared to the CON mixture These cost increases can be attributed to the higher expenses associated with plastic and crumb rubber, including the recycling processes required for both materials, in comparison to natural river sand. Despite the elevated production costs, the use of plastic and crumb rubber offers enhanced environmental benefits relative to the CON mixture, as illustrated in Fig. 13. However, considering mechanical properties, durability, environmental impact, and cost-effectiveness, it indicates that the incorporation of 10% plastic (10P) or 10% crumb rubber (10R) represented optimal options for their application in AAC mixture. These combinations support the development of environmentally friendly construction materials with balanced performance and

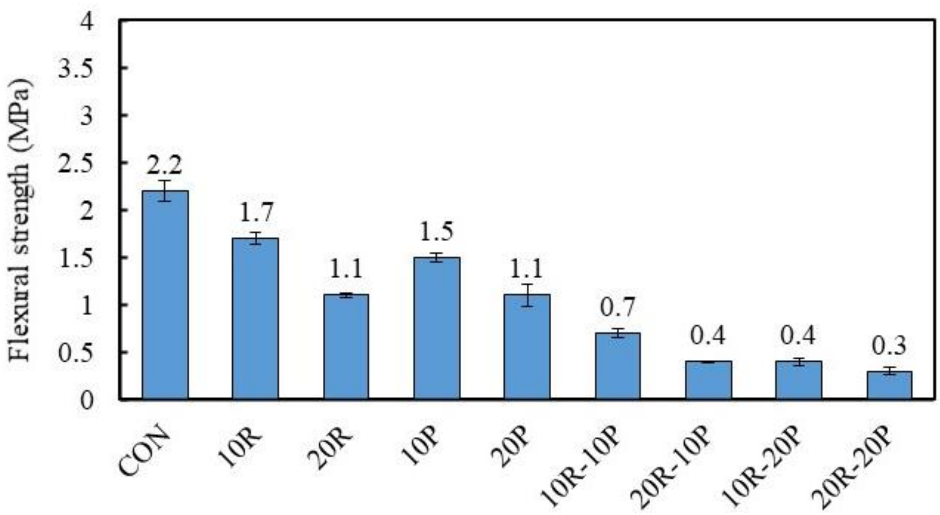

Fig. 11: Flexural strength of alkali-activated concrete.

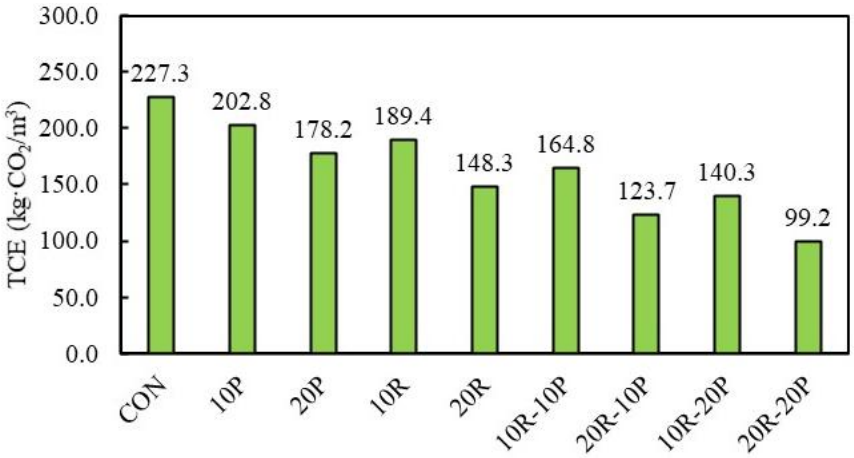

Fig. 12: Effect of crumb rubber and plastic waste on the TCE of AAC.

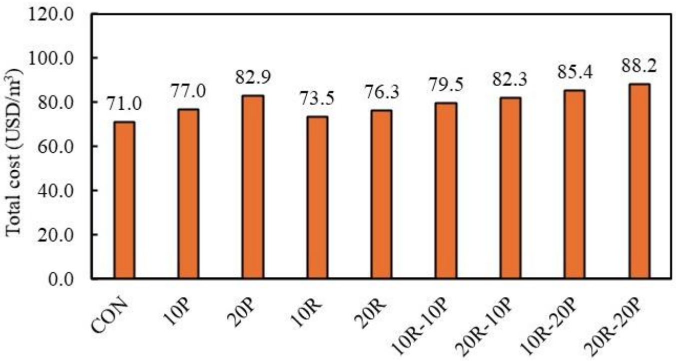

Fig. 13: Total production cost of AAC mixtures.

sustainability benefits.

6. Conclusion

This study investigated the effect of using crumb rubber and plastic waste as aggregates on mechanical properties of alkali-activated concrete. The carbon footprint generated from the concrete was evaluated and discussed. Based on the finding results, the following conclusion can be made.

1. The incorporation of crumb rubber up to 10% by volume decreased the slump and caused a slight reduction in both compressive and flexural strengths. However, it was found that the strain capacity of alkali-activated concrete increased with increasing the crumb rubber content.
2. With the increase in plastic waste content in alkali-activated concrete, modulus of elasticity, compressive strength and flexural strength were reduced. Rubberized concrete containing plastic waste exhibited a greater reduction in the strength compared to normal concrete, primarily due to the adverse effects of the crumb rubber and plastic aggregates. The 28-day compressive strength of 10R-20P and 20R-20P concretes ranged from 5.4 to 6.5 MPa, suitable for the CLSM application.
3. In terms of environmental impact, the incorporation of plastic and crumb rubber as replacement aggregates led to a reduction in total embodied CO_2 emissions. Considering mechanical performance, environmental impact, and cost-effectiveness, the use of 10% plastic or 10% crumb rubber is identified as an optimal replacement level in concrete systems. This approach represents a promising strategy for the development of environmentally sustainable construction materials suitable for practical implementation.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

CRediT Statement

Peem Nuaklong: Conceptualization, Methodology, Investigation, Writing – original draft, Visualization, Funding acquisition. **Kantipok Hamcumpai:** Conceptualization, Methodology, Investigation. **Suraparb Keawsawasvong:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Chanachai Thongchom:** Resources, Writing – review & editing. **Pitcha Jongvivatsakul:** Validation, Resources, Writing – review & editing. **Suched Likitlersuang:** Validation, Resources, Writing – review & editing.

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