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Utilization of recycled concrete aggregates mixed with fly ash as the road base materials in Vietnam

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ABSTRACT

Recycling of construction and demolition waste (CDW) and industrial by-products presents substantial environmental, economic, and social benefits. In developed countries, recycling efforts have been actively promoted for decades, resulting in a high proportion of CDW and industrial by-products being reutilized. However, in developing nations, including Vietnam, the recycling rate of such materials remains relatively low. This study investigates the utilization of the mixtures of recycled concrete aggregates (RCA) and fly ash (FA) as road base materials in Vietnam. In which, FA functions as the fines within the aggregate gradation and is varied from 0% to 20%. A series of laboratory tests was conducted to assess the mechanical behavior of the prepared samples. The findings demonstrate that FA can effectively substitute fines in aggregate mixtures for road base layers, with an optimal content of 5%. The pozzolanic reaction of FA contributes to an enhancement in the California Bearing Ratio (CBR) of RCA-FA mixtures compared to that of natural aggregates, ensuring compliance with required bearing capacity standards, except for specimens containing 20% FA. Moreover, the adhesive mortar generated through the pozzolanic reaction of FA exhibits lower bonding strength than that formed by RCA fines, leading to a lower CBR value and a higher particle breakage index in RCA-FA mixtures compared to RCA-only samples.

1 Introduction

Countries worldwide, including Vietnam, have increasingly prioritized controlling solid waste emissions and promoting using recycled materials to ensure sustainable development. In the context of diminishing natural resources, the reuse of Construction and Demolition Waste (CDW) has emerged as a critical and increasingly popular solution within the global construction industry. Recycling CDW not only provides an efficient alternative to natural materials but also significantly contributes to addressing environmental issues and fostering sustainable development [1–3]. From an environmental perspective, CDW recycling alleviates the pressure on natural resource exploitation, preserves valuable resources, and reduces the amount of solid waste discharged into the environment [2, 4, 5]. This helps minimize negative impacts on ecosystems and mitigates soil, water, and air pollution. From economic and social perspectives, recycling and utilizing CDW

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create job opportunities within the recycling industry and promote the growth of a circular economy. Additionally, CDW recycling extends landfill lifespans, reduces the land area required for waste disposal, and creates more space for other development purposes, such as infrastructure or residential projects [3]. Developed countries such as the United States, Japan, and European nations have recognized these benefits and have actively promoted the recycling of CDW over the past several decades. As a result, the recycling rate of CDW in developed countries has reached impressive levels. For instance, Japan has achieved an almost 100% recycling rate [6]. However, CDW recycling remains limited in developing countries, including Vietnam. According to a 2016 report by the Ministry of Natural Resources and Environment [7], approximately 38,000 tons of solid waste are generated daily in Vietnam, with CDW accounting for 10–15% of the total. However, only 1–2% of CDW is recycled, while the majority is disposed of in landfills or illegally dumped, causing severe adverse impacts [8, 9]. Therefore, implementing solutions to enhance CDW recycling is imperative, and the use of CDW as aggregate in road construction has been widely adopted in previous studies as a viable approach.

Fly ash (FA) is known as a by-product generated from the combustion of coal, which serves as a primary energy source globally. In 2015, coal accounted for 29% of the world's energy supply, and it is projected to remain at 24% by 2035 [10]. The combustion of coal produces coal combustion residues or byproducts, including fly ash, bottom ash, boiler slag, and others, with over 70% of coal ash waste classified as fly ash [11, 12]. Consequently, alongside the promotion of CDW recycling, the recycling of industrial waste, including FA, has garnered significant attention worldwide. In developed countries such as Denmark, Italy, and the Netherlands, the recycling rate of FA has reached 100%, while Japan reports a rate of 96.3% [13]. Countries with high FA production, such as India and China, generate 112 million tons and 100 million tons of FA annually, respectively, with recycling rates of 38% and 45%. As of 2020, Vietnam had 31 operational coal-fired thermal power plants, collectively generating 20.5 million tons of FA annually [12]. Due to increasing electricity demand, the number of coal-fired thermal power plants in Vietnam is projected to rise to 52, with annual FA emissions estimated to reach 30 million tons [14]. However, the recycling rate of FA in Vietnam remains limited due to the absence of policies, and technical standards. Thus, enhancing FA recycling in Vietnam represents a critical area of focus. Previous studies have extensively investigated the potential applications of FA, including its use as an embankment material in road construction [15, 16], for soil stabilization and improvement [17–21], in the production of concrete [22–25], and in asphalt concrete manufacturing [26–28]. In this study, FA is proposed to be used in combination with CDW as a road base material.

Granular materials are usually used for road base construction. The mechanical properties of granular materials are governed by a complex interplay of factors, including particle size distribution (PSD), particle shape, relative density, and type of particle [2, 29, 30]. Among these, PSD plays a particularly crucial role, as it directly impacts the packing density, load-bearing capacity, and overall stability of the material. A key parameter within PSD is the fines content (Fc), typically defined as the proportion of particles smaller than 0.075 mm, expressed as a percentage by weight [2, 30, 31]. Furthermore, Fc also influences the pore structure within granular materials, thereby affecting properties such as permeability, thermal conductivity, and gas transport capacity within granular layers [3, 9, 31]. The use of fine particles derived from CDW as a replacement for natural fine-grained materials provides notable environmental advantages [32]. However, producing fine particles requires a complex process involving crushing and sieving, which necessitates using various types of crushers and advanced technologies. This process incurs additional material preparation costs, presenting an economic challenge for broader adoption. Therefore, this study aims to evaluate the feasibility of using FA as a substitute for fines in the composition of recycled materials for road base construction.

2 Materials and test methods

2.1 Materials

In this study, tested samples were prepared from two recycled materials: recycled concrete aggregates (RCA) and FA, in which, FA has a small particle size and is used to replace fines in the mixtures. The samples were prepared with five different FA content values of 0%, 5%, 10%, 15%, and 20%, respectively. The samples were named as 100RCA, 95RCA5FA, 90RCA10FA, 85RCA15FA, and 80RCA20FA, respectively.

2.1.1 Recycled concrete aggregates

RCA used for testing were produced from waste concrete collected at Thanh Tri landfill. After the waste concrete blocks were collected at the landfill, they were transported to the crushing station to be crushed into RCA. The RCAs were then

transported to the laboratory, where they were sieved to classify them into different particle sizes. In this study, the RCA-graded mixture selected was the type with a nominal maximum particle size of 25 mm, using only aggregates that had particle sizes over 0.075 mm sieve. The designed particle size distributions of RCA-graded samples used in this study were shown in Fig. 1.

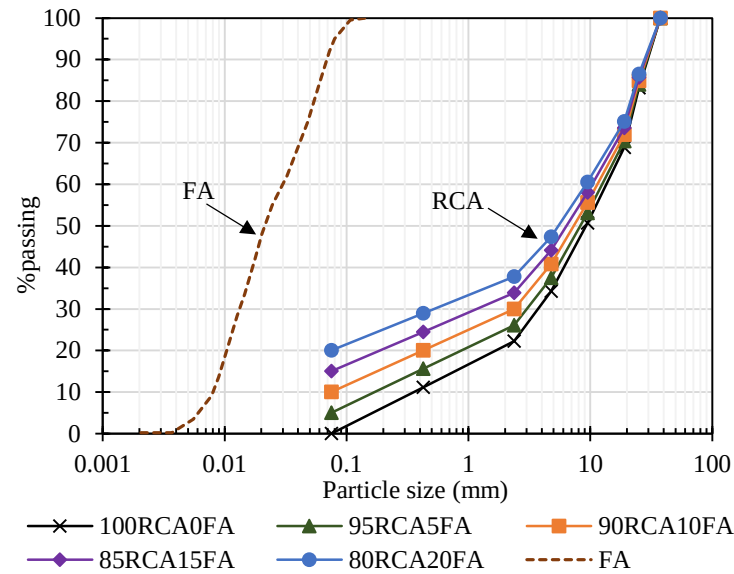


Fig. 1 – Particle size distributions of RCA, and FA samples in this study

Table 1 presents the mass distribution of RCA across different particle sizes, along with the mass of FA used in the preparation of test samples.

Table 1 – The mass of RCA by particle size and the mass of FA used for preparing the test samples

Materials	Particle size (mm)	Mass of samples (g)				
		100RCA0FA	95RCA5FA	90RCA10FA	85RCA15FA	80RCA20FA
RCA	25 - 37.5	842	800	758	716	674
	19 - 25	716	680	644	608	573
	9.5 - 19	911	865	819	774	728
	4.75 - 9.5	821	780	739	698	657
	2.36 - 4.75	600	570	540	510	480
	0.425 - 2.36	553	525	497	470	442
	0.075 - 0.425	558	530	502	474	446
FA		0	250	500	750	1000
Total (g)		5000	5000	5000	5000	5000

The physical properties of tested RCA materials are presented in Table 2.

Table 2 demonstrates that all evaluated properties of RCA materials adhere to the technical standards for road base materials prescribed in TCVN 8859 [33].

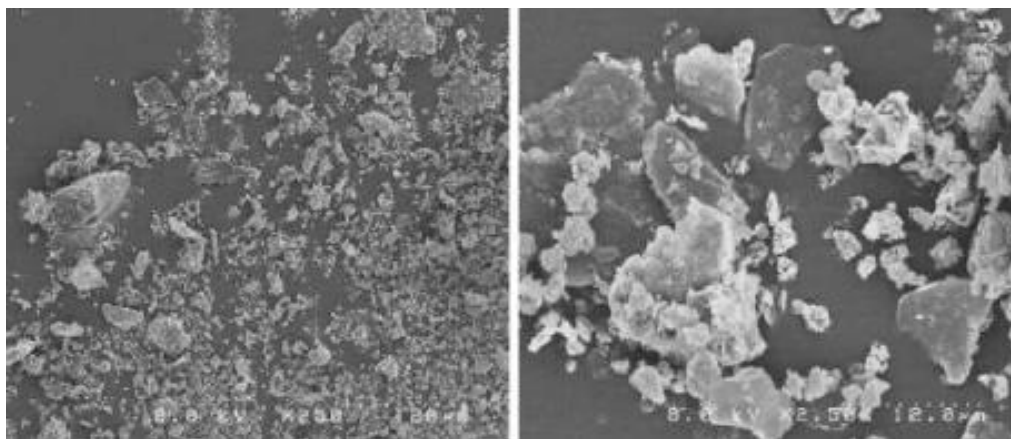
Table 2 – Physical properties of tested RCA materials. Technical requirements in TCVN 8859 (2023) are also given

Properties	Unit	Measured values	TCVN 8859 (2023)		Testing methods
			Type I	Type II	
Specific gravity (G_s)	g/cm ³	2.62	–	–	ASTM C128
Liquid limit (w_L) ^{a)}	%	24.5	≤ 25	≤ 35	ASTM D4318
Plastic limit (w_P) ^{a)}	%	23.0	–	–	ASTM D4318
Plasticity index (IP)	–	1.5	≤ 6	≤ 6	ASTM D4318
Elongation and Flakiness index ^{b)}	%	6.0	≤ 18	≤ 20	TCVN 7572-13
Los Angeles abrasion (LA) ^{b)}	%	31.6	≤ 35	≤ 40	ASTM C131/C131M
Water absorption (w_{abs})					
Coarse aggregate (≥4.75 mm)	%	5.2	–	–	ASTM C127
Fine aggregate (<4.75 mm)	%	8.5	–	–	ASTM C128

^{a)} Measured using samples with particle size < 0.425 mm; ^{b)} Measured using samples with particle size > 4.75 mm

2.1.2 Fly ash

The fly ash (FA) utilized in this study was sourced from the Cam Pha thermal power plant, which employs circulating fluidized bed combustion (CFBC) technology. This combustion process operates within a temperature range of approximately 800°C to 900°C, allowing coal to undergo extended cyclic combustion within the furnace [34, 35]. The particle size distribution of the FA is presented in Fig. 1, illustrating that most particles have diameters smaller than 0.075 mm. This facilitates the blending of RCA and FA to form a well-graded mixture, aligning with the requirements for particle size distribution of road base materials as specified in TCVN 8859 [33]. Figure 2 presents the scanning electron microscope (SEM) images of the FA, revealing that the FA primarily consists of irregularly shaped polygonal particles. Moreover, the FA particles exhibit large surface areas, cohesion between particles, and considerable interparticle porosity. These observations are entirely consistent with findings reported in previous studies [34, 35].

**Fig. 2 – Micro-structures of FA obtained from SEM**

The physical and chemical properties of the FA are presented in Table 3. The specific gravity of FA is notably lower than that of RCA. As presented in Table 3, the FA used in this study contains less than 10% CaO, while the total oxide content ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$) exceeds 70%. Based on these characteristics, the FA is classified as acid fly ash (Type F) in accordance with TCVN 10302 [36] and ASTM C618 [37].

Table 3 – Physical and chemical properties of the tested FA

Properties	Unit	Measured values	Testing methods
Air-dry water content	%	0.4	AASHTO T255
Specific gravity (G_s)	g/cm ³	2.24	AASHTO T85
Loss on ignition (LOI)	%	6.8	ASTM D7348
Retained on 45 μ m sieve	%	29.5	TCVN 4198
Chemical composition:		83.7	TCVN 8262
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	%	6.4	TCVN 141
CaO	%	0.7	TCVN 141
SO ₃	%	9.2	-

2.2 Test methods

2.2.1 Compaction test

The compaction test was conducted in accordance with the Modified Proctor Compaction method specified in TCVN 12790 [38] and ASTM D 1557 [39]. During the test, the samples were compacted in a cylindrical mold with a diameter of 150 mm and a height of 125 mm, using a rammer weighing 4.54 kg with a drop height of 457 mm. The compaction process involved five layers, with each layer subjected to 56 blows, corresponding to a compaction energy (E_c) of 2631 kJ/m³. The relationship between dry density and water content was analyzed to construct the compaction curve. The water content of the samples was adjusted within a range of 1.0–14% by air-drying or adding water.

2.2.2 California bearing ratio test

The California bearing ratio (CBR) test was carried out by the procedures outlined in TCVN 12792 [40] and AASHTO T193 [41]. The samples were compacted into cylindrical molds with a diameter of 150 mm and a height of 125 mm using a rammer (4.54 kg) with a drop height of 457 mm. The CBR test samples were prepared with the optimum water content obtained from the compaction curve. The samples were compacted at three different compaction energies ($E_c = 470, 1400$, and 3050 kJ/m³), achieved by varying the number of blows per layer (10, 30, and 65 blows/layer). After compaction, the samples were soaked in water for 96 hours. After the soaking period, a standard plunger with a 50 mm diameter was then used to penetrate the samples at a rate of 1.0 mm/min until a depth of 12.5 mm was reached. The CBR of each sample was determined according to the criteria specified in the standard method.

2.2.3 Particle breakage measurement

In this study, the particle breakage property was assessed using the particle breakage index (B_g). The samples used for determining B_g values were those that had completed the CBR test. This approach enabled the evaluation of particle breakage at varying compaction energy levels ($E_c = 470, 1400$, and 3050 kJ/m³). After testing, the samples were oven-dried to a constant mass and sieved to measure the retained mass of each particle size sieve. The retained mass was used to calculate the % increase and/or decrease in each particle size fraction. The B_g value was calculated by Eq. (1) following the Marsal method [42].

$$B_g = \sum_{n=1}^i \Delta p d_n \quad (1)$$

where $\Delta p d_n$ is the positive difference in percentage by weight of material retained on the n^{th} sieve between before and after compaction test.

3 Test results and discussion

3.1 Compaction characteristics

Figure 3 illustrates the compaction curves of the tested samples, providing insights into their densification behavior under different moisture conditions.

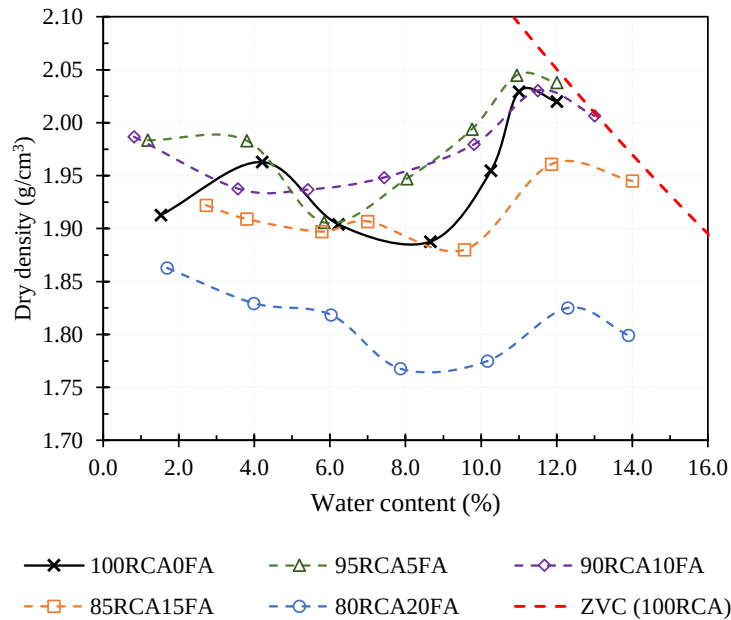


Fig. 3 – Compaction curves of tested samples. Zero air void curve (ZVC) of 100RCA is also given

The observed compaction curves in this study exhibit a similar trend to the typical compaction behavior of RCA, as previously reported by Thai et al. (2022) [2]. Each compaction curve demonstrates the presence of both a maximum dry density (MDD) and a minimum dry density (mDD). Specifically, the mDD value occurs within a moisture content range of 4–10%, while the MDD value is attained at an optimum water content of approximately 10.5–12.5%. Furthermore, a notable trend is observed in which the optimum water content increases as the FA content rises. This phenomenon can be attributed to the intrinsic characteristics of FA, including its fine particle size, high surface area, and porous structure. These properties result in an increased optimum water content, as more water is required to coat the particle surfaces and fill the voids within the material matrix to achieve optimal compaction.

The variation in the MDD value is dependent on the FA or fines content, as illustrated in Fig. 4. It is evident that the sample 95RCA5FA, which contains 5% FA, exhibits the highest MDD value. This observation aligns with findings from previous studies that utilized RCA fines [2, 31]. Specifically, when the FA content increases from 0% to 5%, MDD increases slightly. This can be attributed to the FA particles filling the voids between the RCA particles, thus improving the overall packing and density of the mixture. However, as the FA content rises from 5% to 20%, a significant decrease in MDD is observed. This decline can be explained by the substantially lower specific gravity of FA compared to RCA, which results in a reduced overall density of the mixture. Furthermore, when the FA content exceeds the optimal value, the FA particles not only fill the voids between the RCA particles but also surround them, which interferes with the proper arrangement of the RCA particles [29]. This disruption in particle packing leads to a lower MDD, as FA particles, being lighter, create a less compact structure. When comparing the MDD of the RCA-FA mixtures with the pure RCA (both coarse and fine aggregates are RCA) samples [2] and natural aggregate (NA) samples [43–45], it is evident that the MDD of the RCA-FA mixtures is lower than that of both the NA and RCA samples. This is primarily due to the presence of FA in the RCA-FA mixtures, where FA consists of particles with a significantly lower specific gravity than both RCA and NA particles, thus reducing the overall density of the mixture.

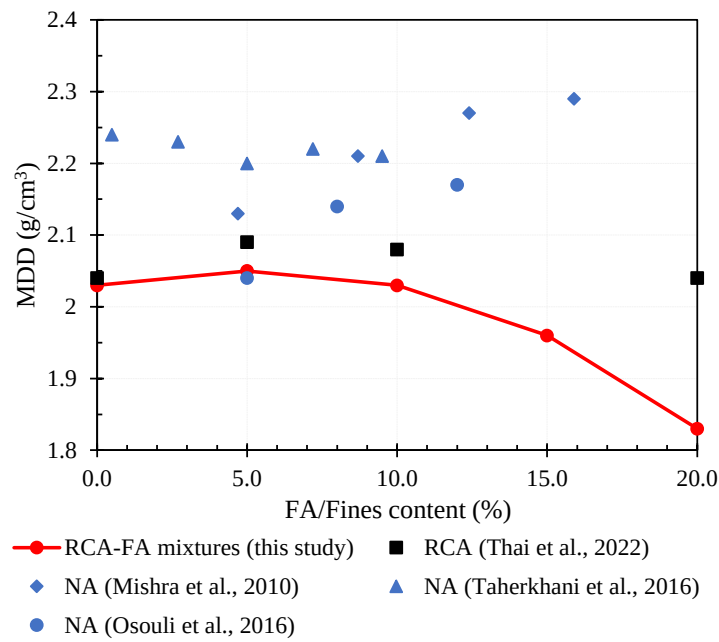


Fig. 4 – Maximum dry density (MDD) values as a function of FA/fines content.

3.2 CBR test results

Figure 5 presents CBR values of the tested samples. It can be observed that most mixtures achieve a CBR value at a compaction level of $K=98\%$, satisfying the requirements for base layer applications in pavement structures following TCVN 8859 [33], except for the 80RCA20FA sample (containing 20% FA). Notably, the 95RCA5FA sample exhibits the highest CBR value at $K=98\%$. This finding is consistent with the MDD results, as the inclusion of 5% FA enhances particle packing by filling the voids between RCA particles, thereby improving the bearing capacity. However, as the FA content increases beyond this optimal threshold, FA particles begin to coat the aggregate surfaces, reducing interparticle friction and disrupting the structural integrity of the mixture, ultimately leading to a decline in bearing capacity. Furthermore, Fig. 5 indicates that RCA-FA mixtures exhibit lower CBR values compared to pure RCA samples.

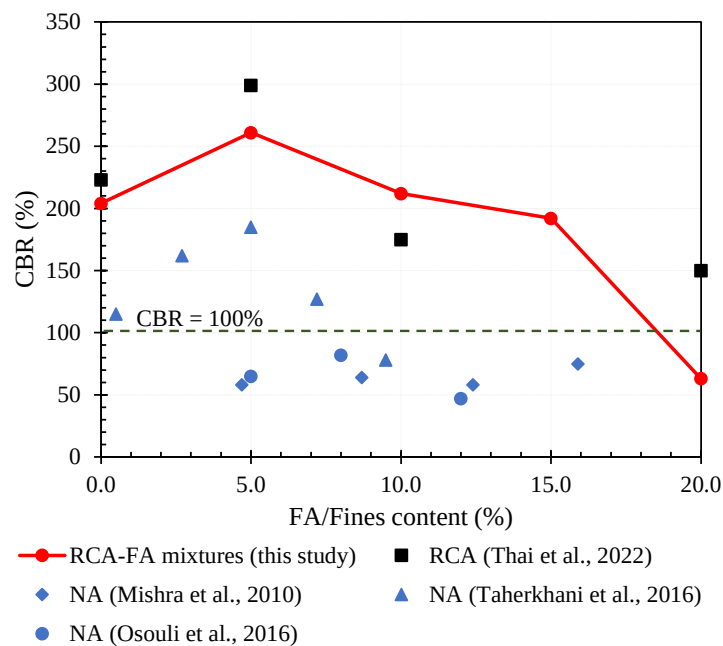


Fig. 5 – CBR values at compaction level of $K=98\%$ as a function of FA/fines content

Previous studies have demonstrated that when RCA is utilized as a subbase material, the residual cementitious particles within RCA, particularly in RCA fines, can undergo further hydration, thereby enhancing the bearing capacity [2, 30, 46]. The cement content in larger RCA particles is lower than that in RCA fines; consequently, the CBR values of RCA-FA mixtures are lower than those of pure RCA samples which include the RCA fines inside. Besides, Fig. 5 also shows that the CBR values of RCA-FA mixtures are higher values than those of NA samples. This can be explained because FA is a pozzolanic material containing siliceous and aluminous compositions as major constituents [47]. When FA is incorporated into RCA, some of the residual cementitious particles present in the RCA undergo hydration, leading to the release of $\text{Ca}(\text{OH})_2$. This $\text{Ca}(\text{OH})_2$ subsequently reacts with the amorphous silica contained in FA through a pozzolanic reaction, forming secondary calcium silicate hydrate (C-S-H) compounds [47, 48]. These newly generated C-S-H phases contribute to the enhancement of the binding properties within the mixture, potentially improving its overall structural integrity and mechanical performance.

3.3 Particle breakage index

The B_g values of the samples with varying compaction energies and different FA/fine content are presented in Fig. 6. It is evident that B_g values are highly dependent on compaction energy, with samples compacted at higher energy levels exhibiting greater B_g values. The FA content also influences B_g values; in samples with a high FA content, FA particles encapsulate RCA particles, forming a cushion layer that reduces inter-particle friction. Consequently, samples with a higher FA content exhibit lower B_g values than those with a lower FA content under the same compaction energy. Thai et al. (2022) [2] determined the B_g values of pure RCA samples with varying fines content at a compaction energy of $E_c = 2631 \text{ kJ/m}^3$ (56 blows/layer), with the results also shown in Fig. 6.

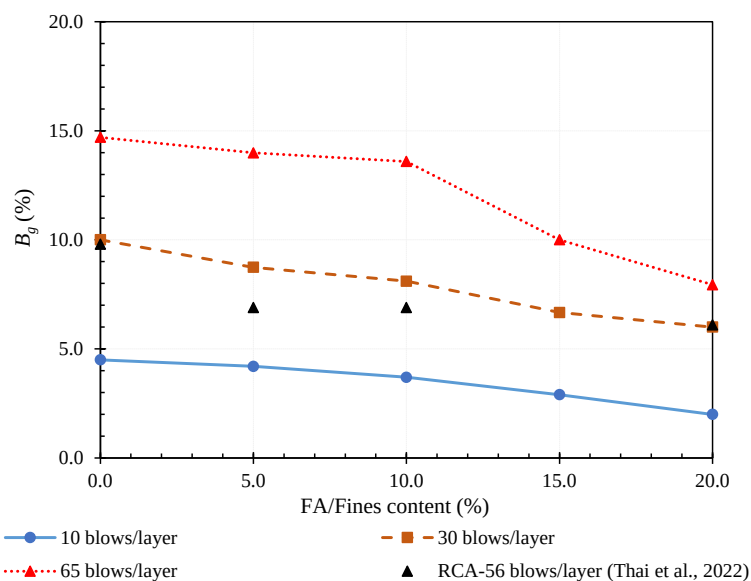


Fig. 6 – B_g values as a function of FA/fines content

Despite being compacted at a lower energy level ($E_c = 1400 \text{ kJ/m}^3$), RCA-FA mixtures exhibited higher B_g values than pure RCA samples. This phenomenon may be attributed to (i) differences in aggregates shape and properties and/or (ii) the characteristics of fines in the mixture. First, regarding the initial shape of the aggregates, more angular particles tend to break more easily. In terms of aggregate properties, RCA particles derived from waste concrete with lower strength are also more prone to breakage during compaction. Second, the characteristics of fines also influence B_g values. RCA fines contain a higher proportion of unhydrated cement particles, which, when mixed with water, form a highly adhesive mortar layer that better coats larger aggregates. This coating reduces inter-particle friction under compaction forces, leading to a decrease in B_g values.

4 Conclusions

This study prepared samples incorporating the mixtures of recycled concrete aggregate (RCA) and Class F fly ash (FA), where FA served as the fines in the aggregate gradation. The FA content varied from 0% to 20%. A series of laboratory experiments, including compaction tests, California Bearing Ratio (CBR) tests, and particle breakage measurements, were conducted to evaluate the mechanical performance of the samples. The following key conclusions are drawn from this research:

- FA can be entirely utilized as a replacement for fines in aggregate mixtures used for road base layers. This promotes the recycling of industrial byproducts and offers economic benefits by reducing the costs associated with fines production.
- The optimal FA content of 5% yields the highest compaction efficiency and load-bearing capacity, as evidenced by the highest maximum dry density (MDD) and the highest CBR value (at $K = 98\%$) reached at FA content was 5%.
- FA is a pozzolanic material that reacts with $\text{Ca}(\text{OH})_2$ released from the hydration of residual cementitious particles in RCA through a pozzolanic reaction, forming adhesive mortar. This reaction enhances the mechanical performance of the mixture. This study indicates that RCA-FA specimens exhibit higher CBR values compared to natural aggregates samples.
- The particle breakage index (B_g) of the material is influenced by multiple factors, including compaction energy, characteristics of aggregate, and the properties of fines. The pozzolanic reaction of FA produces a adhesive mortar that is weaker than that formed by RCA fines, leading to higher B_g values in RCA-FA mixtures compared to pure RCA samples.

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