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Structural behavior of reinforced concrete beams incorporating cocopeat as a partial sand replacement

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ABSTRACT

This study investigated the reinforced concrete beams' structural behavior when the sand aggregate is partially replaced with coconut peat also known as cocopeat. The concrete mixes were prepared by 0, 20, 50 and 100 % variation levels of replacement. Flexural loading tests were conducted on the reinforced concrete beams by also considering the variations in stirrup spacing and main bar diameters. The results indicated that, replacement up to 20 % of sand with hardened cocopeat maintained acceptable structural performance with those with 20 % replacement presented a comparable load bearing capacity and crack resistance to control specimen. Greater than 20 % replacement level exhibited significant reduction in strength and stiffness. The results also revealed that closer stirrup spacing, and larger diameter steel bars overcome the limitations of cocopeat content, improving the beam performance. The study supports the potential use of cocopeat as partial sand replacement in sustainable concrete construction.

KEYWORDS

construction materials • cocopeat • sand content • hardening method • sand aggregate

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Introduction

The depletion of natural sand resources globally, mainly spearheaded by rapid urbanization and infrastructure development, has increased the demand for use of sustainable alternatives in concrete production. In Mekong Delta region of Vietnam, this issue has led to intrusion of government agencies and research institutions, to bring in policies to promote the use of sea sand, crushed sand and recycled aggregates and also revise the existing material standards [1,2]. Despite the efforts, there is a long way to reach the goal of achieving a fully sustainable and structurally viable alternative to natural sand.

Recent studies have explored a wide variety of alternative construction materials including limestone, fly ash, iron slag, thermal ash, recycled aggregates and composite additives such as fiberglass and carbon fibers [3–9]. These materials have exhibited promising outcomes by increasing concrete strength and durability. Addition of steel and synthetic fibers have exhibited improved tensile and flexural strength in reinforced concrete structures [10], whereas material efficiency is achieved from hollow mortar concrete [11]. Natural fibers including coir and jute have been utilised for low strength application-based cements [12–17].

Ongoing studies are investigating the use of local sand (from sand dunes) and sea sand as alternatives to traditional sand in concrete production. Some researchers have studied these sands as replacements for river sand in concrete for rural traffic works, helping to reduce the pressure on sand usage [18–21].

Research from BLDEA in India focuses on "Recent trends in replacing natural sand with different types of sand". The study finds that adding copper slag enhances compressive, tensile, and flexural strength in concrete. Concrete density increases with copper slag use, and the flexural strength of beams improves significantly by 21 to 51 % when replacing sand with copper slag. Additionally, using waste sand from the casting industry, bricks, and mining dust as sand substitutes noticeably improves concrete's compressive and flexural strength [22].

Artificial sand production involves crushing natural rocks such as limestone, laterite, granite, and gravel into particles with a modulus similar to natural sand. This material shows comparable characteristics to natural sand, making it a viable alternative for concrete production. Artificial sand has become popular in Europe and Japan, effectively reducing dependence on natural sand and addressing sand scarcity. It enhances concrete quality and minimizes the environmental impact of sand mining [23–26].

Recycled sand production uses various raw materials, including concrete, bricks, tiles, and soil and rocks from previous construction projects. Manufacturing industries like iron, steel, and glass production also generate waste sand that can be repurposed into recycled sand [27]. Studies indicate that recycled sand has potential applications in construction, building materials, and transportation infrastructure. It can also produce lightweight concrete, offering excellent sound and heat insulation [28–31].

Numerous studies are currently exploring the use of coconut fiber (Fig. 1) as a reinforcing material in concrete and its application in unburnt and pavement bricks [32]. Additionally, projects utilize lightweight concrete for benefits such as weight reduction, soundproofing, insulation, and decoration. Using coconut peat as a sand substitute in concrete offers several advantages, including weight reduction and environmental protection. Ben Tre, recognized for its extensive coconut growing area in Vietnam, reports a projected coconut area of over 78,000 hectares by the end of 2022. Coconut fiber is a significant export product for the province, with exports reaching nearly 49,000 tonnes in 2019 and around 45,000 tons in 2020. A coconut shell consists of 30 % coconut fiber and 70 % cocopeat. Cocopeat, with a size range of 0.01 to 0.46 mm and a density of 1.15–1.46 g/cm^3, is notable for its exceptional water absorption capacity [33,34].

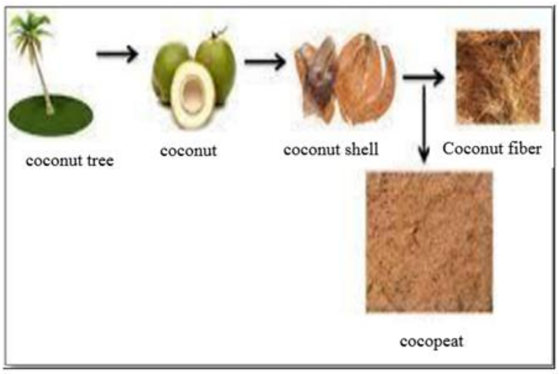

Fig. 1. Coconut fiber and cocopeat. Based on [35]

Numerous studies have investigated the use of coconut fiber as an alternative to sand in concrete. While research on using cocopeat as a sand replacement is limited, it presents a promising area for further exploration. Existing studies have mainly focused on the mechanical properties and durability of concrete with coconut fiber as a partial or complete substitute for sand. Avinash Singh and his colleagues [36] conducted an experimental study showing that incorporating coconut fiber at a rate of 5 % by weight of cement significantly improved the compressive and tensile strength of concrete. Another study examined how coconut fiber affects concrete's mechanical properties and its ability to enhance the bond between concrete and steel reinforcement. This research found that the optimal amount of coconut fiber to add ranged from 0.6 to 1.2 % of the total mass, depending on the desired properties of the final product [37].

Researchers have also explored using the water absorption properties of cocopeat, along with other by-products such as shells and rice husk ash, to develop eco-friendly permeable concrete and produce large-sized unburnt bricks. These products combine cement, stone powder, coal slag, and coconut fiber [38,39].

One study aimed to evaluate the mechanical strength of concrete grade M25, according to Indian standards, by substituting 10 % of sand with cocopeat. The results revealed a notable increase in compressive strength for concrete made with cocopeat treated with a 2 % NaOH solution for 1 h, compared to conventional concrete. On the 28th day, the compressive strength improved by approximately 15.39 % compared to concrete without NaOH treatment [40,41].

Another study assessed the effects of replacing sand with cocopeat in reinforced concrete beams. Researchers tested nine samples of reinforced concrete beams, labeled D1 to D9, with dimensions of 15 × 20 × 120 cm^3. Each beam was reinforced with four D10-CB400-V steel bars and had D6-CB240-T steel stirrups. The researchers used the "hardening method" to incorporate cocopeat as a sand aggregate replacement in the concrete.

Irrespective of numerous studies examining the coconut fiber in concrete, very limited studies have been performed on analyzing the structural performance of reinforced concrete beams when cocopeat is used as sand replacement. The main objective of this study is to evaluate the flexural behavior of the RC beams by varying the cocopeat contents and reinforcement configurations.

The objectives include:

1. Preparation and testing of concrete beams with different cocopeat replacements ratios.
2. Analysis of the influence of stirrups spacing and steel bar diameter on structural performance.
3. Determination of optimal replacement level of sand with cocopeat for maintaining the structural integrity.

Materials and Methods

Materials

Cocopeat, a by-product derived from the husks of coconuts, was used in this study as a partial or full replacement for fine aggregate in the concrete mixtures. Cocopeat has unique properties, including a bulk density of 70–100 kg/m^3, high water retention capacity of 600–800 % due to its porous structure, and an organic content of 20–30 %

lignin and cellulose, making it lightweight. The cocopeat particles were sieved to pass through a 2.5 mm sieve and retained by a 0.63 mm sieve. For comparison, natural river sand served as the control fine aggregate. The sand used in the study had a bulk density of 1600–1700 kg/m^3, a fineness modulus of 2.3–3.1, and particles that passed through a 4.75 mm sieve, with low water absorption, typically around 1–2 %.

Ordinary portland cement (OPC) was the binding material in the concrete mix, with key properties such as a grade of OPC 42.5, a specific gravity of 3.15, and fineness passing through a 90 μm sieve. The cement had an initial setting time of 30 min, a final setting time of about 600 min, and a compressive strength of around 42.5 MPa after 28 days. Crushed stone was used as the coarse aggregate in the concrete, with properties including a maximum size of 20 mm, a bulk density of 1450–1550 kg/m^3, and a specific gravity of 2.65–2.75. Its water absorption was low, at 0.5–1.0 %, and it had a crushing value of less than 30 %, indicating its suitability for structural applications.

The water used in the concrete mix was potable, free from impurities, and appropriate for mixing and curing. Its pH level ranged from 6.5 to 8.5, ensuring neither excessive acidity nor alkalinity. The water-to-cement ratio for all beam samples was maintained at approximately 0.57, ensuring adequate hydration of the cement while providing the necessary workability for the concrete.

Steel reinforcement for the concrete beams was provided according to the specified stirrup spacing for each beam, which ranged between s100, s150, and s150–s200. This reinforcement was essential for ensuring the structural integrity of the beams and improving their load-bearing capacity. High-yield strength deformed steel bars of Grade 60 were used for the reinforcement, which offered high resistance to tensile forces. The diameter of the steel bars varied based on the specific design of each beam, typically ranging from 10 to 16 mm. The yield strength of the steel was approximately 420 MPa, contributing to the overall durability and performance of the reinforced concrete beams under loading conditions.

Hardening process of cocopeat

A total of 120 kg of cocopeat particles hardened with cement was obtained by repeatedly performing the hardening process. The particles were meticulously selected to ensure they remained on the 0.63 mm sieve and passed through the 2.5 mm sieve. Table 1 indicates the optimal water quantity used for hardening the cocopeat with cement.

Table 1. Optimal water content for hardening cocopeat with cement

Cocopeat, g	Cement, g	Optimal amount of water, ml	Finished product, g
100	500	400	760–800

The process of hardening cocopeat with cement involved the following steps:

Step 1: the coconut shells were dried in the sun for one day. A 2.5 mm sieve was used to separate the cocopeat (see Fig. 2).

Step 2: 100 g of cocopeat was measured and wet with 100 ml of water (Fig. 3).

Step 3: 100 g of cement was weighed and mixed thoroughly with the wet cocopeat obtained in Step 2 (Fig. 4).

(a) (b)

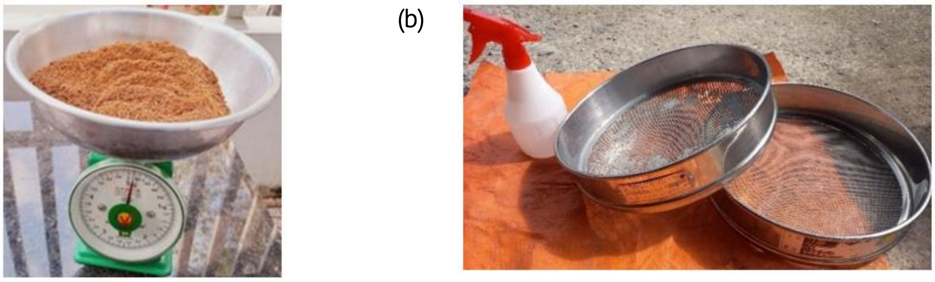

Fig. 2. Cocopeat after step 1 processing: (a) determine the weight of cocopeat, (b) 2.5 mm sieves

Fig. 3. Cocopeat after wetting with 100 ml of water

Fig. 4. Cocopeat after mixing with 100 g of cement

Fig. 5. Combine the cocopeat and cement mixture

Step 4: after 15 min, the mixture is combined. The resulting particles passed through the 2.5 mm sieve and were retained by the 0.63 mm sieve (Fig. 5): (a) cocopeat after wetting (Fig. 3), (b) cocopeat and cement mixture after combining (Fig. 4), (c) final cocopeat and cement mixture after sieving (Fig. 5).
Step 5: the particles that passed through the 1.5 mm sieve were wetted by spraying water evenly over their surface. These particles were mixed with 60 g of cement, repeating the process as in Step 4, until they passed through the 2.5 mm sieve but were retained by the 0.63 mm sieve.
Step 6: the mixture is allowed to solidify for 24 h. Then, the hardened particles are sieved. The final product consisted of particles that pass through the 2.5 mm sieve and retained by the 0.63 mm sieve (Fig. 6).

(a) (b)

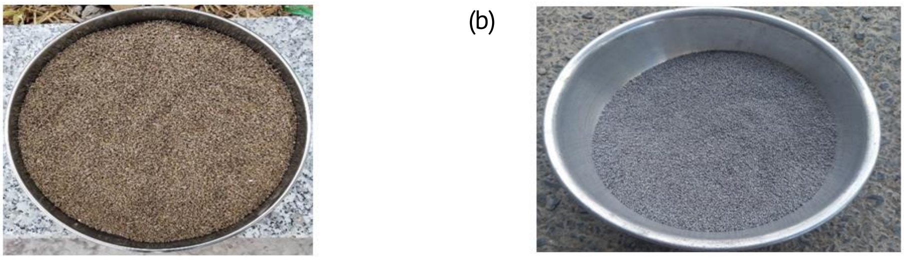

Fig. 6. Cocopeat hardened with cement: (a) finished product remaining on 0.63 mm sieve, (b) finished cocopeat granules have been hardened with cement

Design of reinforced concrete beams

The study involved nine reinforced concrete beams, with variations in stirrup spacing and proportions of cocopeat replacing sand as a fine aggregate and is denoted from D1 to D9 (group 1: D1, D2, D3, D4; group 2: D5, D6, D7, D8; group 3: D9 (Fig. 7)). Table 2 summarizes the beam compositions, detailing the amounts of sand, cocopeat, cement, stone, and water used. The mix design for all specimens was kept constant across each group, with only the fine aggregate (sand/cocopeat ratio) and stirrup spacing varied. Details of each experimental reinforced concrete beam are summarized in Table 2 below.

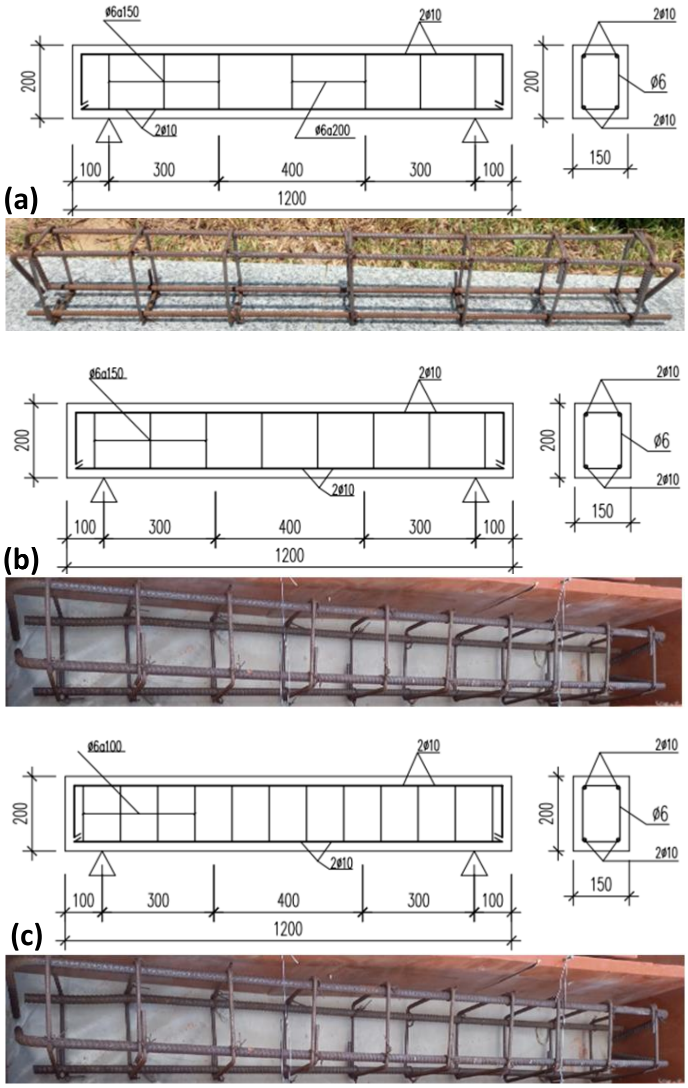

Fig. 7. Design of reinforced concrete beams: (a) group 1 beams, (b) group 2 beams, (c) group 3 beam

Table 2. Details of reinforced concrete beams

Sample groups	Label	Stirrup spacing	$\mu_{cocopeat}$, %	Sand, kg	Cocopeat, kg	Cement, kg	Stone, kg	Water, l
Group 1 Fig. 7(a)	D1	s150-s200	0	22.00	0.00	12.96	43.99	7.38
	D2	s150-s200	20	17.60	4.40	12.96	43.99	7.38
	D3	s150-s200	50	11.00	11.00	12.96	43.99	7.38
	D4	s150-s200	100	0.00	22.00	12.96	43.99	7.38
Group 2 Fig. 7(b)	D5	s150	0	22.00	0.00	12.96	43.99	7.38
	D6	s150	20	17.60	4.40	12.96	43.99	7.38
	D7	s150	50	11.00	11.00	12.96	43.99	7.38
	D8	s150	100	0.00	22.00	12.96	43.99	7.38
Group 3 Fig. 7(c)	D9	s100	50	11.00	11.00	12.96	43.99	7.38

Fig. 8. Formwork and reinforcement processing

Fig. 9. Reinforced concrete beams

The steel reinforcement for the beams was processed according to the specifications outlined in Table 2 and depicted in Fig. 8. After the reinforcement was properly placed and secured, formwork was installed to shape the beams. Once the reinforcement and formwork were ready, concrete was poured into the forms to create the reinforced concrete beams, as shown in Fig. 9.

Testing procedure of reinforced concrete beams

The analysis of concrete samples with varying percentages of cocopeat as a sand replacement was conducted using a JEOL JSM-IT500HR Scanning Electron Microscope. This advanced equipment allows for high-resolution imaging, enabling detailed examination of the microstructural features of the samples. The samples were prepared for optimal imaging, allowing for insights into transition zones, voids, and crack patterns within the concrete matrix.

The experiment assessed various parameters, including the force applied to the beam, the deflection at the midpoint, and the deformation on both sides of the beam. The experiments aimed to evaluate and compare the bearing capacity of each beam. Beams D1 through D9, made of 28–day–old concrete, were subjected to loading using hydraulic jacks applied at two concentrated points until the beams were completely destroyed. Before testing, the reinforced concrete beams were coated with a layer of white lime to facilitate the observation of crack formation and development on the surface, as well as to enable accurate measurement of crack length and width.

Once the setup and equipment were in place, pressure was applied to the structure using a 50-ton hydraulic jack. This jack, operated by an electric pump, was equipped with an oil pressure gauge ranging from 0 to 10,000 Psi (700 Bar or 500 kN). The bearing capacity of the reinforced concrete beams was calculated based on loading levels of 300, 500, 700, 1000, 1400, 2000, and 2500 Psi. At each loading level, the gauge data were recorded, including displacement (V-1), compression zone deformation (PDT-1 and PDT- 2), and tension zone deformation (PDT-3 and PDT-4). It was crucial to carefully observe crack formation and accurately measure their length and width.

Results and Discussion

SEM analysis

The analysis of concrete samples with varying percentages of cocopeat as a sand replacement was conducted using scanning electron microscopy (SEM).

0 % cocopeat sample: SEM images (Fig. 10) show a dense and smooth matrix with well-defined boundaries. The concrete exhibits minimal porosity and few voids, resulting in strong and cohesive bonding within the matrix. The cracks that appear are predictable and minimal. The interfacial transition zones (ITZ) are smooth and well-integrated, and there are few to no micro spheroids, with shapes being well-defined and uniform.

20 % cocopeat sample: SEM analysis reveals a slightly rougher texture with minor irregularities due to the incorporation of cocopeat (Fig. 11). There is a slight increase in porosity and voids compared to the 0 % cocopeat sample, leading to a slight reduction in bonding strength. Crack patterns show minor irregularities. The ITZ displays minor roughness but remains largely cohesive. Few micro spheroids are present, mostly irregular in shape, and the overall shapes are less uniform.

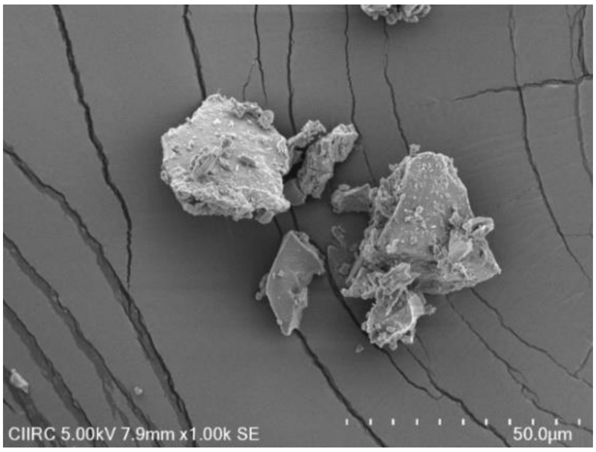

Fig. 10. SEM Image for 0% cocopeat sample

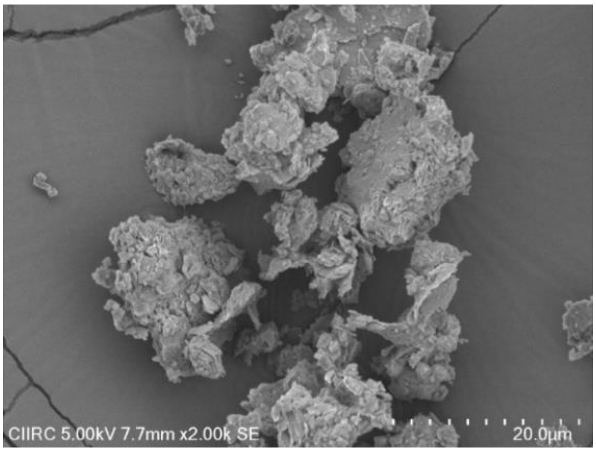

Fig. 11. SEM Image for 20% cocopeat sample

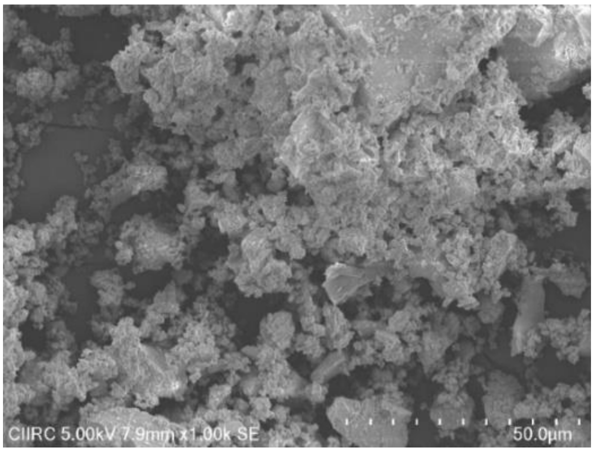

Fig. 12. SEM Image for 50% cocopeat sample

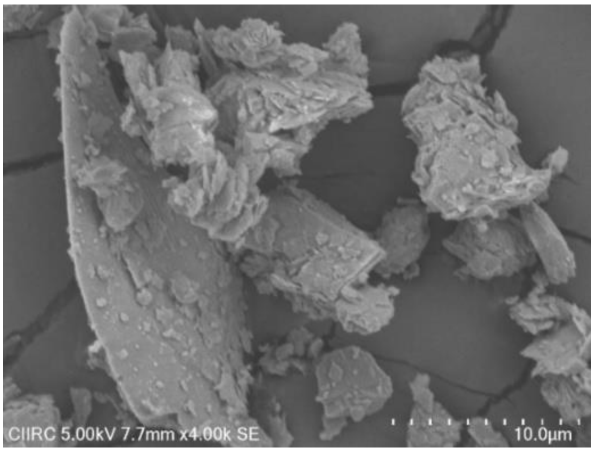

Fig. 13. SEM Image for 100% cocopeat sample

50 % cocopeat sample: SEM images (Fig. 12) indicate a noticeably rougher texture with increased irregularities and surface roughness. Significant voids and higher porosity are evident due to the equal ratio of cocopeat. Bonding quality is reduced with more noticeable disruptions in the matrix. Pronounced and branched cracks develop, and the ITZ shows increased voids and rough bonding. There is an increase in micro spheroids, predominantly irregular, and the shapes are largely irregular throughout the matrix.

100 % cocopeat sample: SEM results show a highly irregular and porous texture due to the complete substitution of sand with cocopeat (Fig. 13). Large voids and very high porosity are observed, resulting in poor bonding quality. Extensive and highly irregular cracks develop. The ITZ is poorly integrated with significant voids. Many micro spheroids are present, mostly irregular in shape, and the shapes within the matrix are predominantly irregular.

Load and vertical displacement relationship between normal concrete beams and beams using cocopeat

In Group 1, observations from Figs. 14–16 revealed key insights into the performance of the reinforced concrete beams. The beams incorporating cocopeat (D2, D3, and D4) displayed reduced displacement compared to the control beam (D1) at equivalent load levels, indicating improved resistance to deformation. Figure 14 shows the setup of the measuring equipment used to capture displacement and deformation. Figures 15 and 16 further illustrate the differences in crack formation and propagation between beams with varying percentages of cocopeat replacement. Notably, the beams with higher cocopeat content showed a delay in crack initiation and slower crack propagation, demonstrating better crack control and overall structural performance compared to the control sample.

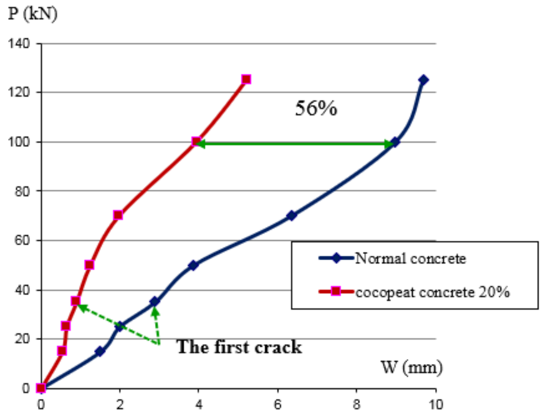

Fig. 14. Vertical displacement of beam D1 and beam D2

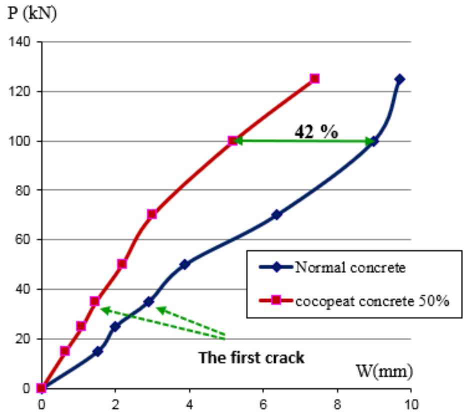

Fig. 15. Vertical displacement of beam D1 and beam D3

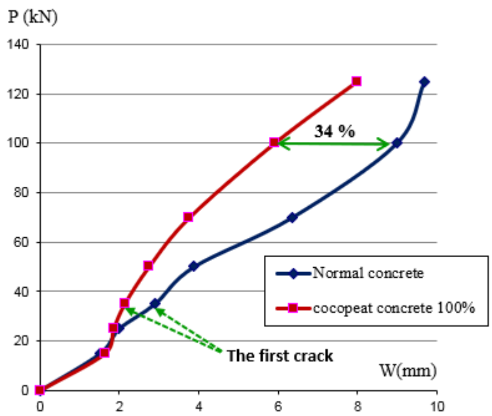

Fig. 16. Vertical displacement of beam D1 and beam D4

In Group 2, observations from Figs. 17–19 highlight that using cocopeat as a replacement for sand in reinforced concrete beams led to reduced displacement compared to conventional concrete beams under the same load conditions. At a load of 100 kN, Beam D6 exhibited 45 % less displacement than Beam D5, while Beam D7 showed a 44 % reduction, and Beam D8 demonstrated a 31 % decrease in displacement. Initial cracking was observed in all beams (D5, D6, D7, and D8) at a load of 35 kN. Significant damage to all beams occurred when the load surpassed 125 kN, marking the onset of structural failure.

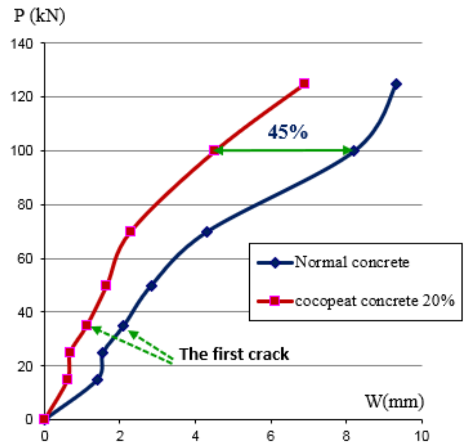

Fig. 17. Vertical displacement of beam D5 and beam D6

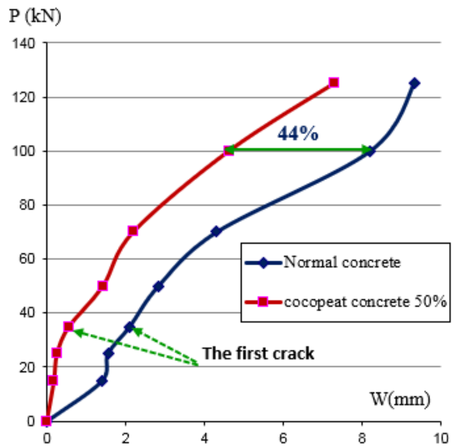

Fig. 18. Vertical displacement of beam D5 and beam D7

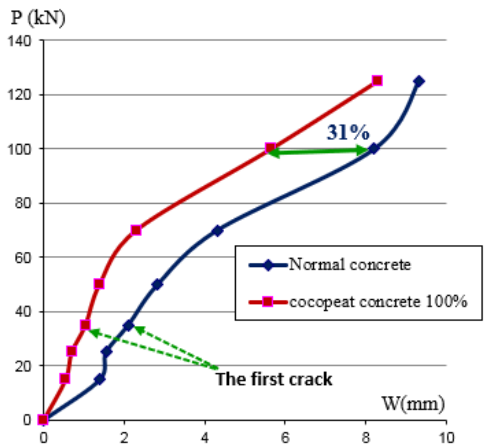

Fig. 19. Vertical displacement of beam D5 and beam D8

This study shows that the "cocopeat particle hardening method" using cement (Fig. 6), following the cocopeat production process described in the one of the previous sections, and the sand / cocopeat ratio (Table 2) have improved the performance of these reinforced concrete beams.

Effect of cocopeat content on vertical displacement in beams

Observations from Figs. 20 and 21 reveal that beams D3 (which incorporates 50 % cocopeat in place of sand) and D4 (which utilizes 100 % cocopeat) exhibit identical vertical displacements. Similarly, the vertical displacement of Beams D6, D7, and D8 is also the same. In Group 1, Beam D2 (with 20 % cocopeat replacing sand) displays the smallest vertical displacement when compared to Beams D1, D3, and D4. In Group 2, Beam D6 (also with 20 % cocopeat replacing sand) shows the least vertical displacement among Beams D5, D6, D7, and D8. The data from Group 1 (Fig. 20) indicate that a 20 % substitution of sand with cocopeat in reinforced concrete beams results in the lowest displacement compared to other configurations. Likewise, the data from Group 2 (Fig. 21) confirm that replacing 20 % of sand with cocopeat in the reinforced concrete beam achieves the smallest displacement, highlighting its highly effective performance.

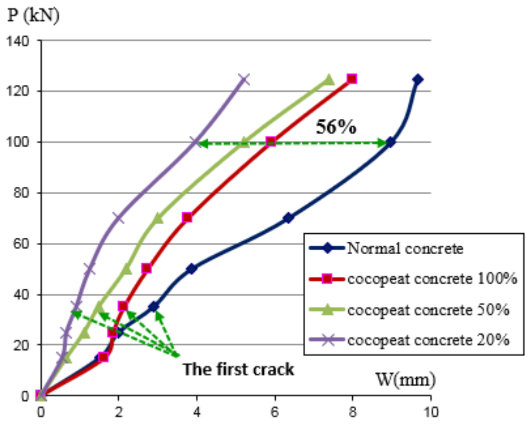

Fig. 20. Vertical displacement of beams D1, D2, D3, D4

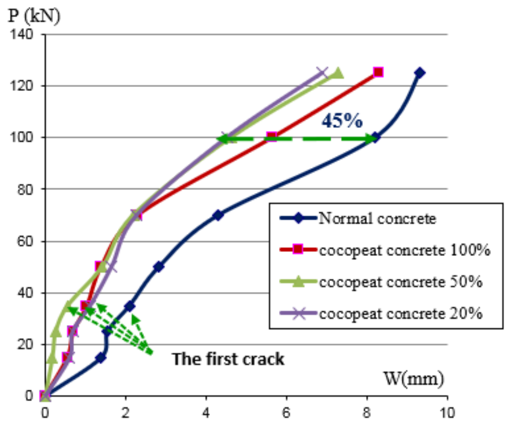

Fig. 21. Vertical displacement of beams D5, D6, D7, D8

Effect of stirrup spacing on vertical displacement of beams

In normal concrete, the beam with a stirrup spacing of 150 mm demonstrates less displacement compared to the beam with a stirrup spacing of 150−200 mm (Fig. 22). When 50 % cocopeat is used as a substitute for sand, the vertical displacements of the beams are similar. However, the reinforced concrete (RC) beam with a stirrup spacing of 100 mm exhibits lower displacement than the RC beam with a spacing of 150 mm. Similarly, the RC beam with a spacing of 150 mm shows less displacement compared to the beam with a spacing of 150−200 mm (Fig. 23). Furthermore, cracks in Beam D9 were first observed at an applied force of 50 kN, while Beams D3 and D7 experienced initial cracking at 35 kN.

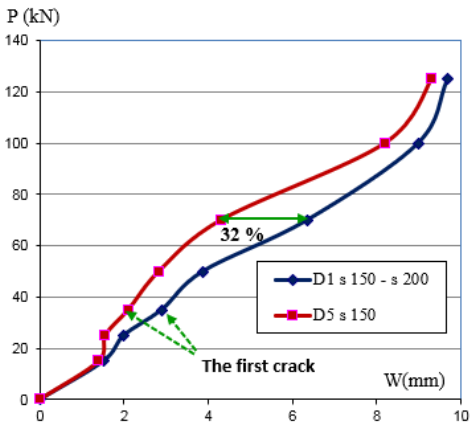

Fig. 22. Vertical displacement of beam D1 and beam D5

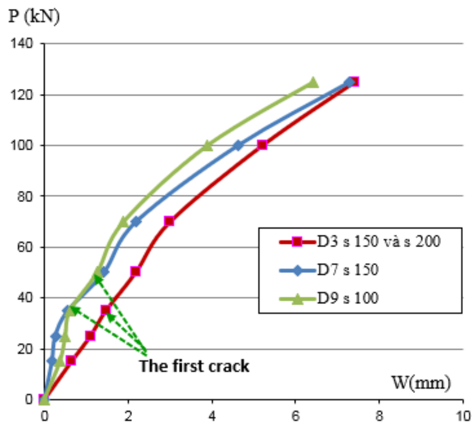

Fig. 23. Vertical displacement of beam D3, D7 and beam D9

The displacement observed in the reinforced concrete beam with stirrup spacings of 150–200 mm (Beam D3) is greater than that of the other beams (Beams D7 and D9), despite all beams having the same concrete aggregate composition. Nonetheless, the displacements of Beams D3, D7, and D9 are in agreement with one another. Additionally, a stirrup spacing of 100 mm leads to delayed crack formation and enhances the load-bearing capacity of the beam prior to failure, in comparison to the other beam configurations.

Load and deformation relationships in beams

Compression zone deformation is shown in Figs. 24 and 25. Based on the diagrams in Figs. 24 and 25, several key observations emerge. The deformation in the compression zone of reinforced concrete beams with varying percentages of cocopeat replacing sand demonstrates similar results across the board. Notably, using cocopeat as a replacement for sand results in reduced deformation in the compression zone compared to normal concrete. When the applied force is below 25 kN, the deformation in the compression zones of all reinforced concrete beams remains nearly identical. However, the most significant differences in deformation occur at a load level of 125 kN. At this load level, the deformation value shows an 85 % difference between Beam D1 (normal concrete) and Beam D2 (20 % cocopeat), and an 89 % difference between Beam D5 and Beam D6.

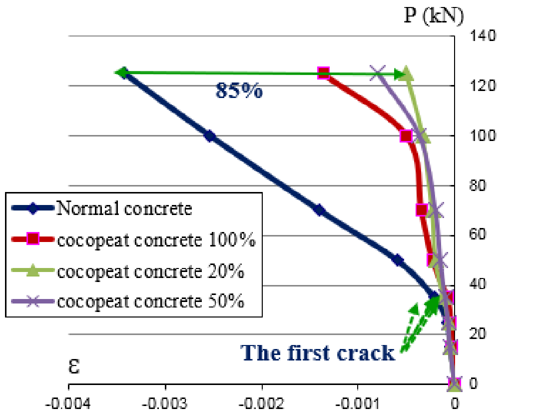

Fig. 24. Compression zone deformation of beams D1, D2, D3 and D4

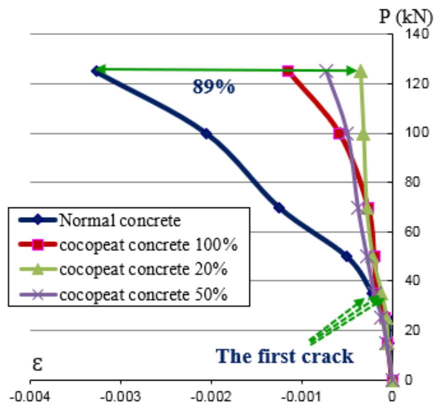

Fig. 25. Compression zone deformation of beams D5, D6, D7 and D8

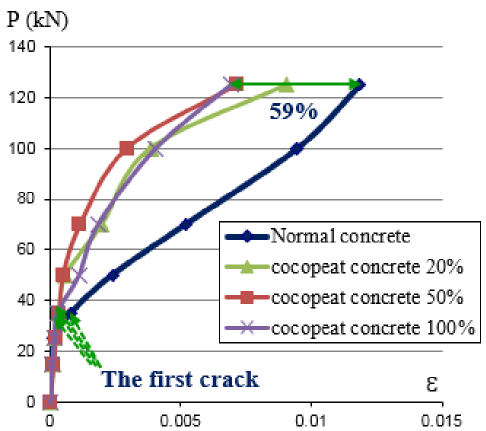

Fig. 26. Tensile deformation of beams D1, D2, D3 and D4

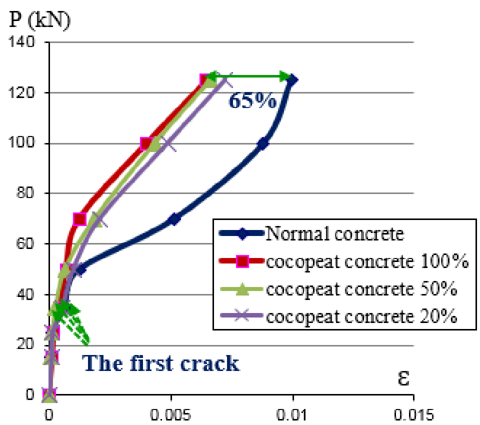

Fig. 27. Tensile deformation of beams D5, D6, D7 and D8

The diagrams in Figs. 26 and 27 reveal several important insights regarding the tensile zone deformation of reinforced concrete beams. The tensile deformation remains consistent across different percentages of cocopeat used as a replacement for sand. Notably, substituting sand with cocopeat leads to reduced tensile zone deformation compared to conventional concrete. For forces applied below 25 kN, the tensile deformation values are similar across all reinforced concrete beams. However, the most significant differences in tensile deformation are observed at a load level of 125 kN, where there is a 59 % difference between Beam D1 (normal concrete) and Beam D4 (100 % cocopeat), and a 65 % difference between Beam D5 and Beam D8. Tensile deformation is shown in Figs. 26 and 27.

Development and propagation of cracks in beams

The test results indicate that all reinforced concrete beams, from Beam D1 to Beam D8, initiated their first cracks under a load of $P = 700$ Psi (equivalent to 35 kN). In contrast, Beam D9 exhibited its initial crack at a higher load of $P = 1000$ Psi (equivalent to 50 kN), as demonstrated in Figs. 28 and 29. These observations are consistent with prior research on crack formation and propagation in reinforced concrete beams subjected to short-term loads [42], as well as studies on deflection and cracking in flexural concrete beams [43]. The cracks predominantly appear at the center of the beam and near the points of force application, with vertical cracks developing in the middle of the beam and diagonal cracks forming at 45 degrees in the support areas. As the load intensifies, both the length and width of these cracks increase, as depicted in Fig. 30. Specifically, at a load of 35 kN, the crack width measures 0.02 mm, which expands to 0.70 mm at a load level of 125 kN, as illustrated in Figs. 30 and 31.

General comments

The SEM results demonstrate that as the percentage of cocopeat increases in the concrete mix, the texture becomes progressively rougher and more porous. The addition of cocopeat leads to a noticeable increase in voids and irregularities within the matrix, which adversely affects the bonding strength and structural integrity. Concrete with 50 and 100 % cocopeat shows significant reductions in cohesiveness and an increase in irregularities and micro spheroids, leading to less predictable crack patterns and reduced overall performance compared to the 0 and 20 % cocopeat samples:

1. The deformation in both tensile and compressive zones of reinforced concrete beams, whether using varying percentages of cocopeat as a replacement for sand or using normal concrete, shows comparable values.
2. Replacing sand with cocopeat in reinforced concrete beams leads to reduced deformation in both tensile and compressive zones compared to beams made with normal concrete.
3. All tested reinforced concrete beams exhibit greater tensile strain compared to compressive strain.
4. The maximum deformation in the compression zone for beams using cocopeat instead of sand is 1.37 %, significantly lower than the deformation in beams made with normal concrete, which is 3.27 % (equivalent to $\varepsilon_{cu} = 3.5$ % for normal concrete).

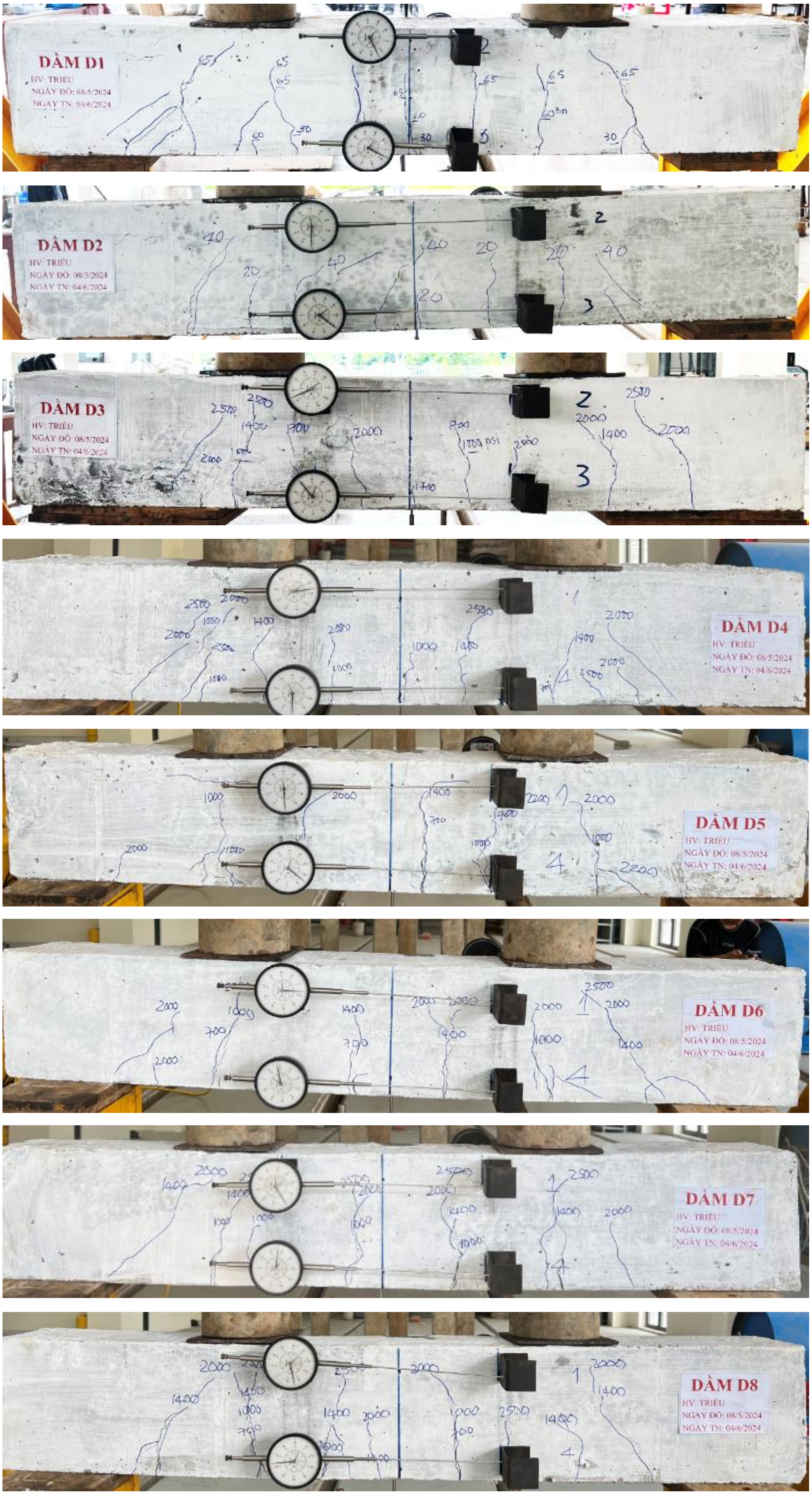

Fig. 28. Formation and propagation of cracks in reinforced concrete beams

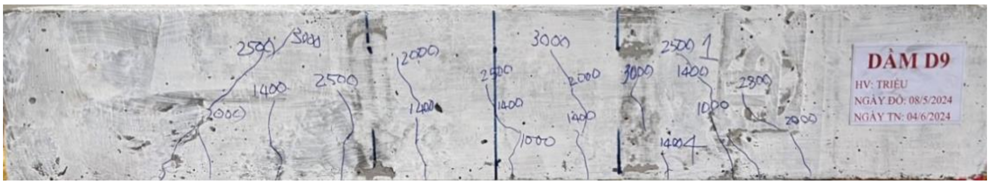

Fig. 29. Cracks of D9 reinforced concrete beams

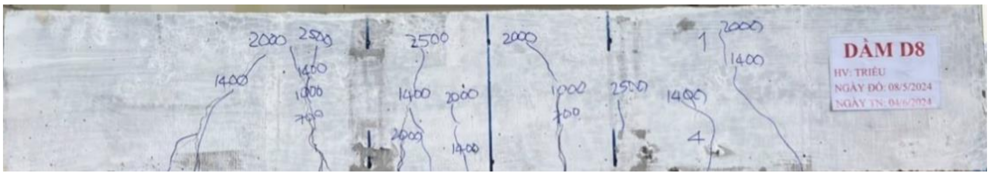

Fig. 30. Cracks of D8 reinforced concrete beam

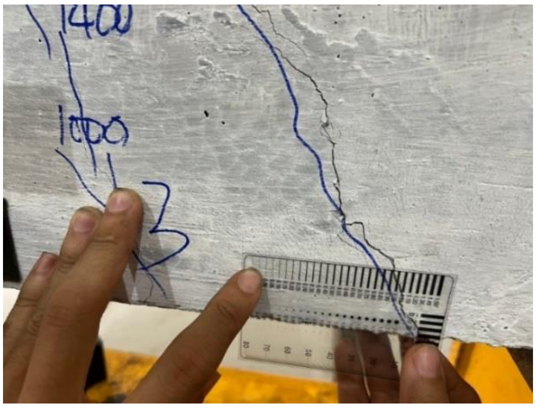

Fig. 31. Measure the crack width of D8 reinforced concrete beam

These findings align closely with the results from the study [43]. For instance, cracks appeared in all normal concrete B15 beams under compression when a load of 35 kN was applied, and damage occurred in the beams subjected to loads exceeding 110 kN.

Conclusions

This study demonstrates that cocopeat particles, hardened with cement, can effectively substitute sand in concrete production:

1. The SEM results reveal that increasing the proportion of cocopeat in the concrete mix results in a rougher and more porous texture. Higher cocopeat content introduces more voids and surface irregularities, which negatively impacts the bond strength and structural stability. Concrete samples with 50 and 100 % cocopeat exhibit significant increases in irregularities and micro spheroids, leading to unpredictable crack patterns and reduced performance compared to those with 0 and 20 % cocopeat.
2. Specifically, replacing 20 % of the sand with hardened cocopeat in reinforced concrete beams yields load-bearing capacities comparable to those of normal concrete beams.
3. The study found that the characteristics of deflection, deformation, and crack formation and propagation in reinforced concrete beams with a stirrup spacing of 200 mm were similar to those with stirrup spacings of 100 and 150 mm. This similarity underscores the practical implications for the design and arrangement of stirrups in reinforced concrete beam construction.

4. Replacing sand with cocopeat at varying levels 20, 50, and 100 % led to an increase in vertical displacement between spans of the reinforced concrete beams. However, this increase was less pronounced compared to beams made without cocopeat.
5. Cracking was observed when the load reached 35 kN, and all beams from D1 to D8 failed under loads exceeding 125 kN.

The encouraging results of using cocopeat as a sand substitute in concrete highlight its potential for sustainable construction. A focused roadmap for future research can include several key areas: optimizing cocopeat proportions by experimenting with varying ratios (e.g., 10, 30, 50 %) to determine the best mix for strength and durability; assessing long-term performance under different environmental conditions and evaluating how the material ages over time; and conducting a life-cycle cost analysis to compare cocopeat-enhanced concrete with traditional methods, focusing on material and labor costs. Additionally, researchers should measure the environmental impact by analyzing reductions in carbon footprint and resource usage and exploring waste reduction opportunities.

CRediT authorship contribution statement

Thanh-Quang-Khai Lam : writing – review & editing, investigation, supervision; **Minh-Trieu Nguyen**: conceptualization, investigation, data curation; **Hoang-Khang Lam** : investigation, writing – original draft; **K.S. Sreekeshava** **:** SEM analysis, writing – editing.

Conflict of interest

The authors declare that they have no conflict of interest.

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