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Lightweight aggregate concrete: a study on production and structural application

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Abstract

This research paper investigates the production of lightweight aggregate concrete (LWAC) and its experimental performance within the context of bending structures. The objective is to elucidate the advantages and prospective applications of LWAC, particularly in structural components subjected to bending forces. This study encompasses the development and testing of two distinct concrete mix formulations and four beam specimens, encompassing of both conventional aggregate concrete and lightweight aggregate concrete, for comparative analysis. The mechanical characteristics of the lightweight aggregate concrete mixture showed a likeness to conventional concrete concerning slump. Nevertheless, they exhibited a lower compressive strength, reduced dry weight, and an accelerated ultrasonic pulse velocity. Notwithstanding these distinctions, they conform to the prescribed criteria for strength and slump as stipulated in EN206-1, ASTM C330/C330M-17a, and ACI 318-11 standards. Furthermore, the performance assessment of lightweight aggregate concrete within flexural beam structures reveals that the LAWC10 and LAWC12 beam specimens are entirely suitable for structural utilization. This suitability is clear in terms of both their load-bearing capacity and deformations (displacements).

KEYWORDS- *Lightweight aggregate, Concrete, Bending structure*

1. INTRODUCTION

Lightweight Aggregate Concrete (LWAC) is a specialized formulation wherein lightweight aggregates are utilized as a replacement for conventional aggregates. Lightweight aggregate concrete, as the name suggests, is a type of concrete wherein traditional aggregates are replaced with lightweight ones, such as fly ash, micro-sized bubbles, or expanded perlite. The key advantages of LWAC include a reduced load-bearing capacity because of its lower specific gravity, yet retaining the necessary durability, resulting in potential savings in transportation and building costs. Structurally, its porous composition also offers notable insulation against heat and sound. Moreover, LWAC also boasts significant fire-resistance capabilities, reducing potential fire-related threats. Given its attributes, LWAC is well-suited for various structural components, including walls and floors. Its combination of reduced weight and insulation advantages makes it a preferred choice for homes, skyscrapers, and projects which prioritize weight and energy efficiency.

The deginition of Lightweight Aggregate concrete varies, creating occasional ambiguities when discussing the material. There is a divergence in terms of its strength, density, and specific classification. For instance, the ACI 213R-14 [1] guideline characterizes structural lightweight concrete (SLC) by setting a lower limit for cylinder strength at 17 MPa and a balancing density of between 1120 and 1920 kg/m^3. Yet, specified density concrete (SDC) doesn't have a strength prerequisite, but typically exhibits a density range of 800 to 2240 kg/m^3. SLC that showcases a 40 MPa compressive strength after 28 days is deemed as high-strength lightweight concrete. European standards approach this differently. Here, the lightweight concrete is represented as a material in EN 206 [2], and its use is governed by EN 1992-2 [3]. The minimum strength class stands at 12Mpa, otherwise, it is 80 Mpa for maximum strength. According to Vietnamese Standards TCVN 9029:2017 [4] and TCVN 5574:2018 [5], the use of concrete grades is limited from B1.0 to B40.

In recent years, the research, development, and application of environmentally friendly artificial lightweight materials as a substitute for natural materials have attracted significant attention from the scientific community. A prime example is the recycling and use of fly ash, a byproduct from coal-fired power plants. Two primary methods exist for producing artificial lightweight materials: melting [6,7] and cold bonding [8,9]. Of these, the cold bonding method is considered more energy-efficient and environmentally friendly. The vast amount of fly ash discharged from coal-fired power plants needs to be used effectively. Concurrently, there is a high demand for natural materials in construction, particularly with the current shortage of natural stones. Therefore, researching and developing artificial aggregates is an required solution at present. By utilizing fly ash with a small amount of cement as a binder, this artificial lightweight material emerges as an eco-friendly choice for lightweight concrete, simultaneously helping to consume large quantities of fly ash [10].

A review of previous studies shows that the specific gravity of these aggregates is typcially 16-46% lower compared to standard weight aggregates, leading to an increased water absorption capacity. Sintered fly ash concrete exhibits notable characteristics in terms of its fresh state, mechanical strength, and longevity. Concretes formulated with sintered fly ash aggregates report a 28-day compressive strength of between 27-74 MPa and densities from 1651-2017 kg/m^3. The fineness of fly ash directly affects the physical attributes of the resulting aggregates. Among the range of binders, bentonite stands out as the most frequently employed, with a favored dosage ranging from 15 to 35% of the powder content. The angle of the pelletization disc can fluctuate between 35° to 70°, while its speed can vary from 20 to 50 rpm. Typically, sintering temperatures oscillate between 1000 to 1200°C. The aggregates produced are predominantly spherical, and their specific gravity ranges from 1.33 to 2.35. The loose bulk density lies between 765 and 936 kg/m^3. While some literature highlight an absorption capacity ranging from 0.7 to 33.9%, commercially available aggregates typically absorb water at rates of 10 to 25%. Concrete produced with these parameters can achieve compressive strengths of 23.12 to 74 MPa and a density range of 1651 to 2017 kg/m^3. Additionally, the tensile strength and modulus of elasticity can vary from 2 to 4.9 MPa and 16.7 to 30.65 GPa, respectively. All these parameters offer promise for the formulation of structural concretes, which often show structural efficiencies surpassing conventional, denser concretes. In terms of durability, some studies highlight that the permeability and chloride penetration levels of sintered fly ash lightweight aggregate concretes (LWAC) are superior to those of traditional aggregate concretes. This is attributed to a more resilient interfacial transition zone (ITZ) present in these concretes. Compared to standard aggregate concrete, the thickness and quality of the ITZ in sintered fly ash aggregate are notably improved. Beyond mere mechanical interlocking, a chemical interaction was also detected in the ITZ of these sintered fly ash aggregates. An elevation in the sintering temperature bolsters the pozzolanic reactivity between the aggregate and paste. The occurrence of internal curing within the ITZ further refines its quality. In comparison, dry aggregate concretes display better characteristics than both pre-wetted and cold-bonded aggregate concrete. The resilience of these fly ash-enhanced concretes suggests they are aptly suited for structural implementations [11]. Another review by Yash Agrawal et. showed that LWAC can be used in the sustainable construction industry and reduce waste by using it as a natural aggregate in concrete to maintain environmental sustainability [12]. This literature review has presented research findings on lightweight aggregate concrete regarding its properties such as fresh concrete, hardened properties (compressive strength, splitting tensile Strength, Flexure Strength, Modulus of elasticity, ultrasonic pulse velocity), durability (drying shrinkage), chloride penetration, carbonation, fire resistance, freeze-thaw resistance, environmental life cycle assessment (LCA), and general applications of LWAC.

Based on these reviews, it's apparent that the production of concrete from lightweight aggregates has garnered significant attention from researchers. In particular, there has been a distinct focus on using lightweight aggregates derived from recycled industrial byproducts for creating concrete in structural elements. Investigating how these lightweight aggregates impact the properties of lightweight concrete, in line with current standards, is crucial to ensure that this type of material meets the structural application requirements.

2. MATERIAL AND EXPERIMENT METHOD

2.1.Materials

The raw materials used for the production of lightweight concrete are imported from factories and distributors in the Mekong Delta region. Table 1 clearly illustrates the mechanical properties of these materials. In the batching process, fly ash plays a significant role, sourced from the Duyen Hai I coal-fired power plant in Tra Vinh. Portland Cement Type PCB 40 was employed as a binding agent, serving the production of lightweight aggregates and concrete. The stone of size 10x20mm has a concentration of aggregates in the 5-10mm sieve, accounting for 92.86%, with a maximum size (Dmax) of 20mm and a minimum size (Dmin) of 10mm. The sand used has a fineness modulus of 1.63.

Table 1. The properties of the used materials

Material	**Stone 10x20**	**Lightweight Aggregate**	**Sand**	**Cement**	**Fly ash**
Specific Gravity (kg/m^3)	2690	2371	2604	2997	2215
Volumetric Mass (kg/m^3)	1485	1002	1483	-	-
Water Absorption (%)	0,34	17,6	0,8		
Compressive	-	1,87	-	-	-

Material	Stone 10x20	Lightweight Aggregate	Sand	Cement	Fly ash
strength (MPa)					

Results from Tuan et al., [10] indicate that lightweight aggregates with a volumetric weight of around 1g/cm^3, water absorption ranging from 12.84-16%, and a rupture compressive strength of up to 1.14 MPa can be produced. The 28-day compressive strength of the lightweight concrete reaches between 17.5-25.1 MPa with a water-to-cement ratio of 0.30. The dry volumetric weight of the lightweight concrete significantly decreases, registering at 1.869 g/cm^3. The water absorption rate of lightweight concrete is higher compared to that of conventional concrete. Hence, in this research, the lightweight aggregate used in the study was produced from fly ash and cement at a weight ratio of 90/10 [1]. The produced lightweight aggregate (Figure 1) has a concentrated aggregate size in the 5-10mm sieve range and is approximately 25% lighter than natural aggregate (stone 10x20). The individual compressive strength of the lightweight aggregate reaches a strength of 1.87 MPa.

Figure 1. Lightweight Aggregate

2.2. *The design of the concrete mix*

In the current investigation, two distinct concrete mix designs were developed, specifically, Normal Aggregate Concrete (NAC) and Lightweight Aggregate Concrete (LWAC). Comparative results between these samples provide insights into the inherent characteristics of lightweight aggregate concrete.

Drawing upon previous research, the Water-to-Binder ratio was uniformly maintained at 0.35, as referenced in [13], with the slump tailored to lie within the 60-80 mm bracket. Moreover, the benchmark mixture employed 10x20 aggregates. When transitioning to lightweight aggregates, these 10x20 aggregates were seamlessly replaced with lightweight counterparts, ensuring volumetric consistency relative to the density of the concrete. A detailed breakdown of the components for each concrete mixture is tabulated in Table 2. Due to the pronounced water absorption capacity of the lightweight aggregates, a pre-soaking step in tap water was incorporated. This spanned a 24-hour period, prior to the concrete pouring process.

Table 2. The design of the concrete mix

No.	Mix	Water to binder ratio (W/B)	Stone 10x20	Lightweight Aggregate	Sand	Cement	Water
1	NAC	0,35	1255,4	-	725	383,9	134,3
2	LWAC			778,5			

2.3. Design of structural bending samples:

To assess the prospective utility of LWAC for structural components, a comparative experimental study was undertaken. This involved the fabrication of two beam specimens from LWAC and an analogous set of two specimens from Normal Aggregate Concrete (NAC) for bending tests. All beams maintained uniform dimensions of 150mm x 200mm x 2200mm. The confinement steel utilized was D6 with a consistent spacing of 100 mm, and the longitudinal reinforcement comprised 4 bars of type 4F10. Comprehensive details of the beam configurations are elucidated in Table 3 and illustrated in Figure 2. It is imperative to note that throughout the research, conditions were standardized to ensure that all specimens predominantly exhibited flexural failure modes. Based on the tensile test results for steel, the yielding strengths of the steel for D6, D10, and D12 are 316MPa, 522MPa, and 557MPa, respectively.

Table 3. Details of beam samples

No.	Concrete strength		Dimension			Reinforcement bars	
	Comp. (MPa)	Bend. (MPa)	Long (mm)	Width (mm)	Height (mm)	Confinement Bars (Stirrups)	Longitudinal reinforcement bars

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NAC10	27,5	3,3	2200	150	200	D6a100	4D10
NAC12	27,5	3,3	2200	150	200	D6a100	4D12
LWAC10	23,5	1,9	2200	150	200	D6a100	4D10
LWAC12	23,5	1,9	2200	150	200	D6a100	4D12

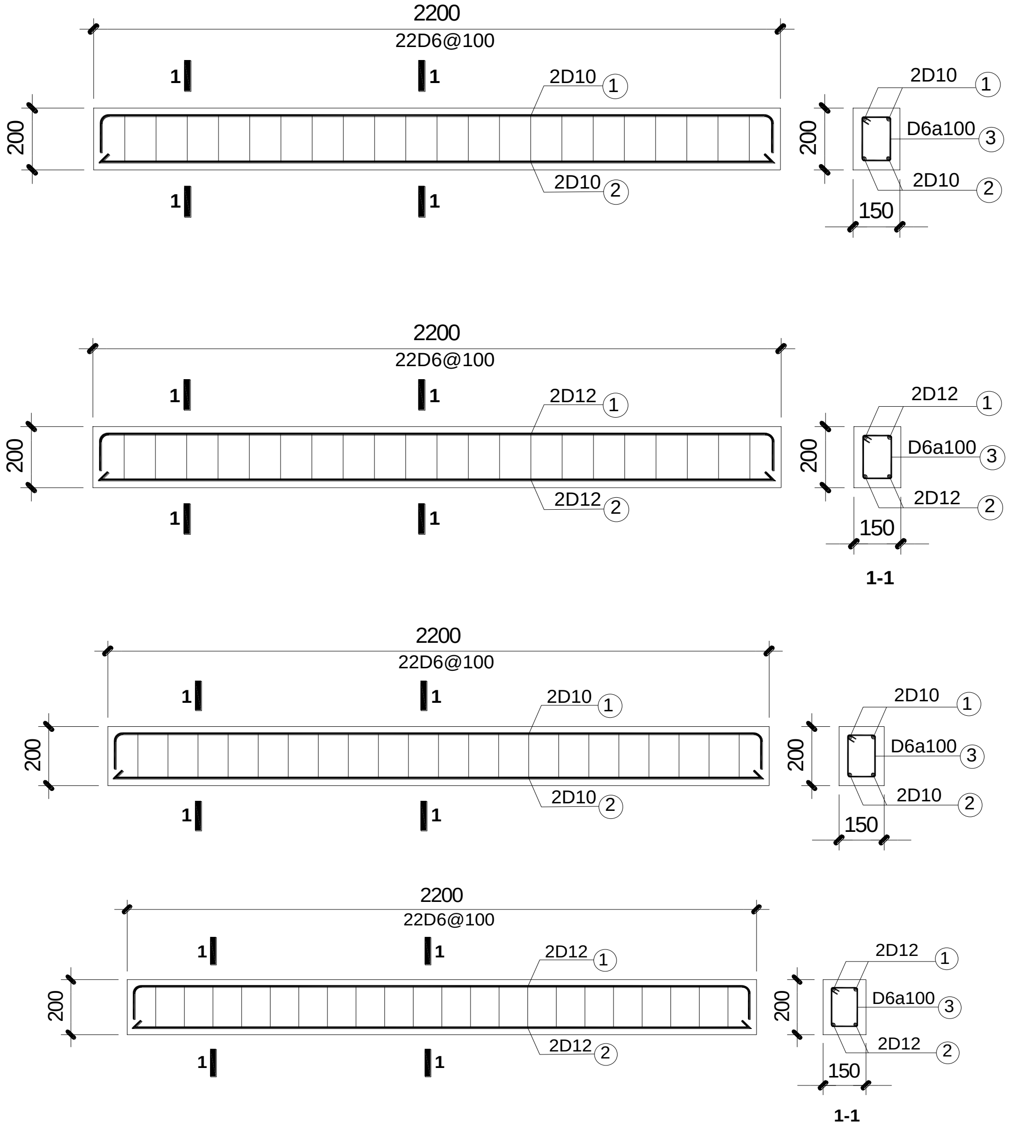

Figure 2. Details of beam samples

(a) NAC10, (b) NAC12, (c) LCAW10, (d) LCAW12

2.4.Experimental method

2.4.1 Lightweight Aggregate concrete

Concrete blending procedure: Initially, sand and cement were mixed uniformly for 3 minutes. Thereadter,, half of the designated water was added to create a mortar mixture. Subsequently, the coarse aggregate (either 10x20 stone or lightweight aggregate) was introduced, followed by the remaining half of the water. Once blended, theslump was assessed in accordance to [14]. The prepared mixtures were poured into molds, setting them up for various tests like compressive strength [15], bending tensile strength [16], split tensile strength [17], and ultrasonic pulse speed [18].

2.4.2. Beam samples:

The beam specimens were fabricated and evaluated at the Construction Laboratory of Can Tho University. The testing configuration is depicted in Figure 3, highlighting the use of three Linear Variable Differential Transducers (LVDT) and the applied load. The evaluation procedure entailed exposing the samples to two concentrated vertical forces through a load-transfer beam. The displacements at these points were monitored using the LVDTs, while the external load was progressively increased.

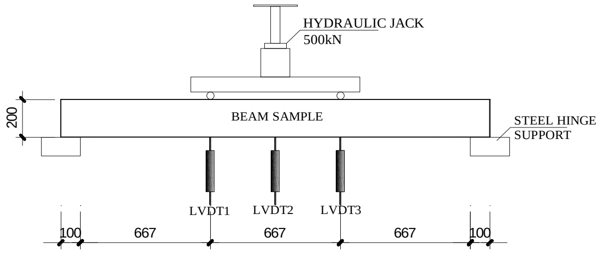

Figure 3. Setting for the beam bending test.

3. RESULTS AND DISCUSSION :

3.1. Slump and Dry Unit Weight of Concrete.

From Figure 4, it can be observed that the aggregate was evenly distributed throughout the concrete mass, with no signs of layering or segregation. Additionally, as shown in Table 5, the slump of the concrete produced in this study was 7cm. This shows that all the concrete mix proportions meet the design requirements, falling within the acceptable range of 6cm to 8cm. From this, it can be inferred that the workability of lightweight aggregate concrete is similar to that of the reference concrete NAC.

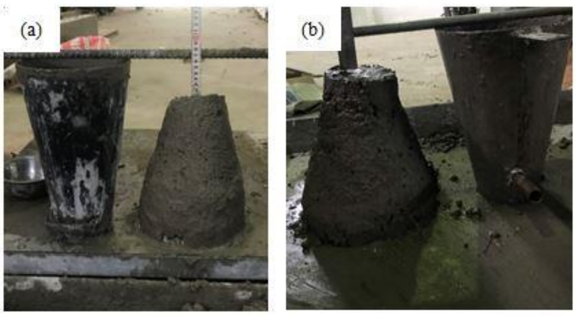

Figure 4. Slump of the concrete samples; (a) CNA; (b) LWAC

Based on the data from Table 4, it is clear that the Dry Unit Weight of the different concrete samples varied between 1950-2321 kg/m^3. Compared to NAC, the lightweight aggregate concrete saw decline in its Dry Unit Weight by approximately 15%. This decrease can be attributed to the lightweight aggregate's specific weight of 2371 kg/m^3, which is notably lesser than that of the 10x20 stone, pegged at 2690 kg/m^3. When the 10x20 stone was replaced with lightweight aggregate in our study, the resulting dry volumetric weight was 1950kg/m^3 for LWAC. This qualifies the concrete as 'lightweight' [19], adhering to the benchmark of having a weight under 2000 kg/m^3

Table 4. Slump and Dry Unit Weight of the assessed concrete.

STT	Mix Proportion	Slump (mm)	Dry Unit Weight of Concrete (kg/m^3)
1	NAC	70	2321
2	LWAC	70	1950

3.2.Compressive strength

Table 5 depicts the evolution of the concrete's compressive strength over a 28-day cycle. Observationally, there was a notable increase in compressive strength from day 7 to day 28 for all tested concrete samples. The reference concrete sample, NAC, exhibited a higher compressive strength compared to the LWAC mixed samples. All samples were tested at both day 7 and day 28. Results show that byreplacing the 10x20 stone with lightweight aggregate resulted in a reduction of compressive strength by 18% to 26%. This discrepancy highlights the distinct influence of the aggregates on the concrete's strength. This reduction is attributed to the porous structure and the high water absorption rate (17.6%) of the lightweight aggregate compared to the 10x20 stone (which has only a 0.34% absorption rate), consequently affecting the compressive strength. The results also indicate that concrete samples using lightweight aggregate met the technical standards for compressive strength [20,21], particularly the minimum strength requirement of 17 MPa at 28 days.

Table 5. Compressive Strength of Concrete

STT	Mix Proportion	Compressive strength (MPa)	
		Day 7	Day 28
1	MAC	19,7	28,7
2	LWAC	14,4	23,5

3.3.Flexural Strength and Splitting Tensile Strength of Concrete.

The results in Table 6 show that the flexural strength of concrete ranged from 1.5 MPa to 3.3 MPa, with the highest flexural strength reaching 3.3 Mpa (NAC) and the lowest being 1.5 MPa (LWAC). The flexural strength of the lightweight concrete mix reached 75% at day 7, decreasing to 57% at day 28 when compared to the flexural strength of the concrete mix using 10x20 stone. In addition, the tensile strength at day 28 ranged from 1.9 MPa to 2.5 MPa for theNAC and LWAC samples, respectively. The results indicate a difference when substituting the 10x20 stone aggregate with lightweight aggregate, leading to a reduction in the tensile splitting strength by 24%.

Table 6. Flexural Strength and Splitting Tensile Strength of Concrete.

STT	Mix Proportion	Flexural Strength (MPa)		Splitting Tensile Strength (MPa)
		Day 7	Day 28	
1	NAC	2,0	3,2	2,5
2	LWAC	1,5	1,9	1,9

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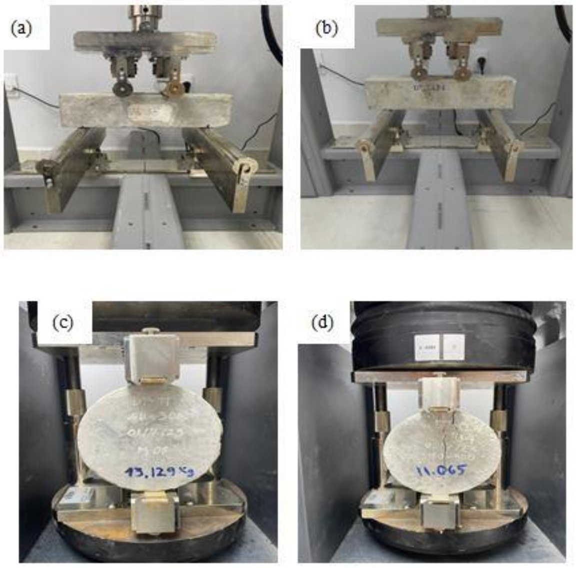

Figure 5. Concrete Splitting Tensile Strength; (a) CNA; (b) LWAC

3.4.Ultrasonic Pulse Velocity

Figure 6 and Table 7 illustrate the ultrasonic pulse velocity outcomes for various concrete mix formulations. Notably, the ultrasonic pulse velocity of the NAC concrete mix exhibited a consistent reduction, falling around 11% lower than that observed in the lightweight aggregate concrete formulations. These results consistently parallel the directional trends identified during the compressive strength testing of the concrete specimens.

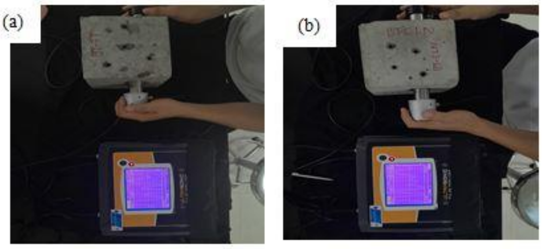

Figure 6. Ultrasonic Pulse Velocity Testing; (a) CNA; (b) LWAC

Table 7. Ultrasonic Pulse Velocity of Concrete

STT	Mix Proportion	Ultrasonic Pulse Velocity (m/s)
1	NAC	3175
2	LWAC	3571

3.5 Structural bending test:

The results of the bending tests are detailed in Table 8. Under initial lateral loading, flexural cracks appear in the tension zone of the mid-section, where the internal moment was at its maximum value in the region with the highest moment distribution (theoretically). The onset of this primary crack shows the cracking strength of the specimens. Meanwhile, the ultimate strength is derived from the force-displacement curve, as depicted in Figures 7, 8, and 9 and summarized in Table 8.

Table 8. Bending test results.

No.	Compressive strength R_n (MPa)	Cracking point		Ultimate point	
		Cracking Strength f_{cr}(kN)	Displacement (mm)	Ultimate Strength f_{cr}(kN)	Displacement (mm)
NAC10	28.19	16.1	5.7	34.6	43.9
LWAC10	26.15	15.9	5.7	32.7	39.8
NAC12	28.19	25.7	6.9	66.1	39.9
LWAC12	26.15	22.8	6.5	64.5	38.5

The results indicate that the crack resistance of the tested beam samples ranged from 15.9kN to 25.7kN. The experimental results in section 3.3 show that the tensile strength of the concrete was relatively low compared to the cracking strength of the beam samples. This confirms that the D10 and D12 longitudinal steel bars in the tension zone primarily bear most of the tensile stresses under the influence of external forces., leading to improved tensile crack resistance in the tension region. Conversely, the influence of the longitudinal bars becomes more pronounced when comparing results from beam samples using different diameter steel bars, D10 (16.1 MPa, 15.9 MPa) and D12 (25.7 MPa, 22.8 MPa). With a lower flexural tensile strength compared to Normal Concrete NAC, the results clearly show that the crack resistance of LAWC10 and LAWC12 beams is lower than that of regular concrete beam samples by between 1.2% to 11%. Meanwhile, the recorded maximum displacement (deflection) ranging from 5.7 to 6.9 for the beam samples is nearly equivalent across the board.

When the load continued to increase and the displacement was controlled at the LVDT3 position (middle of the beam), additional flexural cracks formed and expanded in areas with the highest tensile stresses, spanning from LVDT1 to LVDT3. Upon reaching the peak load values, ranging from 32.7kN to 66.1kN, these flexural cracks widened further. For beam samples employing D10 longitudinal bars, cracks in the tensile region broadened and extended towards the compression region, with the ultimate strength of these beam samples registering at 34.6 kN and 32.7 kN for the NAC10 and LAWC10 beams, respectively. Furthermore, the NAC10 beam displayed greater ductility compared to the LAWC10 beam, as evidenced by its 43.9 mm displacement relative to the 39.8 mm displacement of the latter. This discrepancy can be attributed to the tensile and compressive strength of the regular NAC concrete compared to the lightweight aggregate concrete (LAWC). The destructive behavior because of bending is clearly evident in the middle zone of the beam (from LVDT1 to LVDT3). The flexural cracks continue to propagate and extend towards the compression zone, while the cracks caused by shear damage remain relatively limited. Even as the neutral axis shifts (changing tension and compression regions) due to the structural behavior gradually transitions to the “plastic” stage.

On the other hand, for the beam samples that employed D12 longitudinal bars, at the mid-span cross-sections, damages, and the spalling of the concrete were observed in the compression zones, as shown in Figures 8 and 9. This shows that the concrete's compressive strength in the compression zone was inadequate to withstand the contributed compressive stresses. This deterioration led to a gradual reduction in the load-bearing capacity of these beam samples. The ultimate strength values and displacements upon reaching the peak state for these samples were nearly equivalent, with a relatively small deviation of 2.4% for force and 3.5% for displacement.

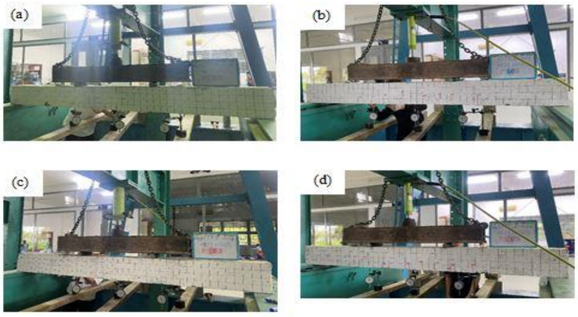

Figure 7. Bending test of specimen at cracking load
(a) NCA10; (b) LWAC10; (a) NCA12; (b) LWAC12

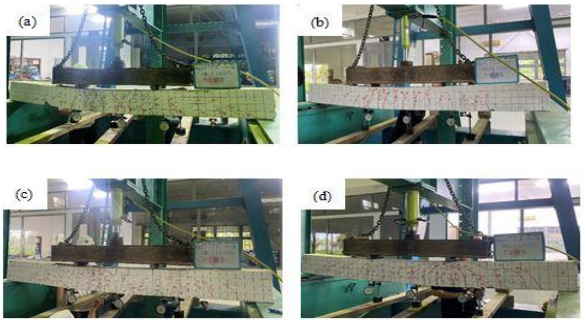

Figure 8. Bending test of specimen at peak load
(a) NCA10; (b) LWAC10; (a) NCA12; (b) LWAC12

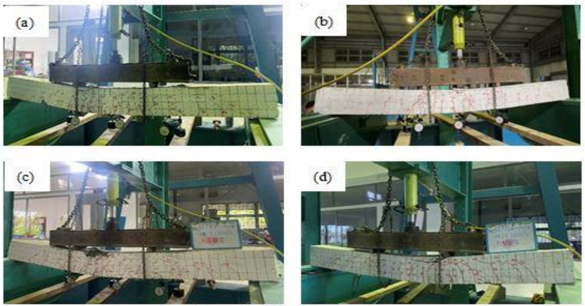

Figure 9. The end of the test
(a) NCA10; (b) LWAC10; (a) NCA12; (b) LWAC12;

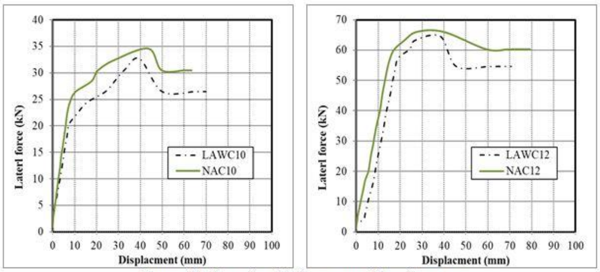

Figure 10. Forced – Displacement of bending test

4. CONCLUSION:

In this research, we evaluated the properties of lightweight aggregate concrete (LAWC) and the behavior of lightweight aggregate concrete beams (LAWC10, LAWC12). Comparing with the standard concrete samples, the research affirmed the following conclusions:

1. The slump of the lightweight aggregate concrete mixtures is equivalent to that of conventional concrete and falls within the acceptable range. Meanwhile, the dry volumetric weight of the lightweight aggregate concrete mixtures was 15% lower than that of conventional concrete and was therefore considered lightweight according to the EN 206-1: 2013 standard, which requires a dry volumetric weight of concrete to be below 2000 kg/m^3.
2. The compressive strength of the concrete developed steadily from day 7 to day 28 for all concrete mixtures. The lightweight aggregate concrete met the compressive strength requirements for lightweight concrete according to the ASTM C330/C330M-17a and ACI 318-19 standards. Moreover, the splitting tensile strength of the lightweight concrete showed a growth trend similar to flexural strength and was 24% lower when compared to conventional concrete.
3. The ultrasonic pulse velocity of the lightweight aggregate concrete mixtures was 11% higher than that of the conventional concrete mixtures.
4. When applied to flexural members, it was found that beams made of lightweight aggregate concrete had a cracking strength that was 1.2% to 11% lower than beams made of conventional concrete. However, the ultimate strength values of the lightweight aggregate concrete beams were 2.4% to 5.5% lower than those of the conventional concrete beams. Furthermore, the displacement at the ultimate strength for all beam specimens was almost equivalent.

This suggests that the development of lightweight aggregate concrete beams could potentially replace conventional concrete beams in conditions with appropriate loading requirements and where a lower structural weight is desired.

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