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Flexural and Shear Behavior of Reinforced Sustainable Concrete Beams Incorporating Waste Walnut Shells as Lightweight Aggregate

Omar Shamal Farhan [a,*], Sheelan Mahmoud Hama [b], Omer K. Fayadh [a]

[a] *Department of Architecture, Al-Nahrain University, Baghdad, Iraq*
[b] *Department of Civil Engineering, University of Anbar, Ramadi, Iraq*
Corresponding author: [*]dr.omer.shamal@nahrainuniv.edu.iq

Abstract*—Several investigations have been conducted on the application of walnut shells as aggregates; however, these investigations have primarily focused on mechanical properties and have not evaluated the impact of using walnut shells as aggregates on the flexural or shear behavior of R.C. beams to determine whether the resulting concrete is appropriate for structural use. Thus, the impact of using walnut shells (WSs) as coarse aggregate in place of aggregate on the flexural and shear behavior of beams was investigated in this work. In this work, the performance of reinforced concrete beams with 5%, 10%, and 15% by volume of walnut shell aggregate (WSA) substituted for natural coarse aggregate is examined. The toughness, ductility, stiffness, and compressive strength of the concrete specimens were assessed experimentally. According to the results, the compressive strength decreased gradually as the WSA concentration increased, ranging from 30 MPa for the control mix to 21 MPa at a 15% replacement level. Notable gains in toughness and ductility were noted despite this decrease. With a moderate improvement in toughness of up to 16.7% and the most significant increase in ductility of up to 117%, beams containing 5% WSA demonstrated higher energy absorption and post-yield deformation capability. WSA did, however, also result in a reduction of early stiffness, especially at lower replacement amounts. Overall, the results show that, at optimal replacement levels (≤10%), walnut shell aggregate can improve the ductility and toughness of concrete while preserving a respectable compressive strength. For lightweight concrete applications, WSA provides an environmentally responsible and sustainable substitute that complements current initiatives for resource-efficient building techniques.

***Keywords*—Walnut shell; lightweight aggregate; flexure; shear; strength; deflection.**

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I. INTRODUCTION

Lightweight aggregate concrete has superior earthquake performance, acoustic (sound), and thermal insulation when compared to conventional concrete. There are two types of lightweight aggregates: artificial and natural. While natural lightweight aggregates include things like pumice, oil palm shell, coconut shell, walnut shell, and more, artificial lightweight aggregates include things like expanded clay, expanded shale, and sintered fly ash [1].

Concrete's decreased density results in a lower deadload on concrete buildings, which lowers handling and transportation expenses. Better heat and thermal insulation are also features of the reduced density, which also lowers the possibility of earthquake damage. Nevertheless, there are several disadvantages to employing lightweight aggregates. For example, when lightweight aggregate is used as a substitute for aggregate in a certain mix, the strength characteristics of the mix are usually low since the lightweight aggregate is weaker and more porous [2].

It is possible to benefit from the weight reduction property by using lightweight aggregates and at the same time avoid the decrease in strength by partially replacing the regular aggregates with lightweight aggregates. In this way, it can be used concrete with hybrid aggregates with properties that meet the strength requirements and achieve economic gains. If the lightweight aggregates are from waste, this will achieve additional environmental gains [3].

The agriculture sector has a number of waste disposal-related problems, and these problems are becoming worse every day [4]. Agricultural waste is either burned, which releases large volumes of greenhouse gases into the atmosphere and releases minute combustion product particles, or buried, which causes harmful chemical compounds to leach through decomposition processes [5]. One of the wastes that has a high potential for creating eco-friendly materials for the building industry is agricultural waste. One form of agricultural waste that can be transformed into useful resources is walnut shells, which is used in the production of certain building materials to promote sustainability in the building sector. Concrete aggregate can be replaced with walnut shells and other agricultural waste [6]. In an effort to increase sustainability in the building industry, experts have recently focused on developing building-friendly materials from walnut waste. Because of its low specific gravity, walnut shells can be used as inexpensive agricultural waste products to create building materials [7].

Walnut shells are a great alternative to coarse aggregate in concrete. Three layers of varying porosity make up the cortex's microstructure: the heterotrophic cell layer, the wrinkled cell layer, and the stratum corneum, which is the densest on the outside and the most porous on the inside [8], [9]. The development of a lightweight, environmentally friendly wet-mix shotcrete by replacing natural coarse gravel with nut shells (walnuts) was detailed by Cheng et al. [10]. The fresh concrete mixed with different volume fractions of walnut shells was first evaluated for its mechanical properties (i.e., tensile and compressive strength), pumpability, and workability (i.e., slump, pressure drop, and rebound rate), as well as comparisons with plain concrete. While the slump and pressure drop slightly decreased, the concrete's compressive and tensile cracking strengths fell as the walnut shell was added. Additionally, the right amount of walnut shell may increase the shooting ability of fresh concrete with a higher build-up thickness and a low rebound rate.

Hama and Abdulghafor [6] investigated the impact of partially replacing coarse aggregate with lightweight aggregate on the load-deflection behavior and other characteristics of concrete. First, waste walnut shell was utilized in place of natural aggregate, followed by porcelain aggregate. Both types are considered lightweight aggregates. 25% to 100% volumetric replacement percentages were employed.

Furthermore, 10% of the leftover glass powder was used as a substitute for cement. Measurements were made of compressive strength, splitting tensile strength, and dry density. A one-way slab cast for 50% replacement was also subjected to a four-point flexural test. The results show that, regardless of the lighter aggregate's source, substituting it for natural aggregate lowers density, compressive strength, and splitting strength [11]. Slabs using lightweight aggregate exhibited more deflection after failure than the reference slab. 50% WA concrete showed a noticeable 62.57% decrease in strength when compared to the reference slab, whereas 50% porcelainized concrete demonstrated a slight 8.91% increase in strength. The diameter of the crack at failure was greater in concrete with coarse walnut aggregate than in the control sample. Concrete that had been impregnated with porcelain failed at the same time, although the cracks were less than the reference crack [3].

Hilal et al. [12] investigated the use of walnut shells as a coarse aggregate substitute in self-compacting concrete using 10 different volume fractions, ranging from 5 to 50% with each increment of 5%. The fresh and hardened properties of SCC were analyzed for all mixes. The results showed that all measured parameters declined as the WS volume% % increased. On the other hand, lightweight self-compacting concrete (LWSCC) can reach a fraction volume of WS of at least 35%. SFD. At a 35% WS ratio, compressive and bond strengths of 35 MPa and 6.55 MPa, respectively, were achieved.

In their work, Kamal et al. [13] utilized walnut shells, an agricultural waste, to partially replace fine aggregate in concrete properties. The results showed that, at a water-to-cement ratio of 0.38, walnut shells can be used as a partial replacement for fine aggregate up to 30% without compromising the structural concrete's compressive strength. Walnuts are utilized to make dietary supplements and desserts in every Iraqi city. A substantial area of land is required for disposal because the waste that the walnut shell generates can vary from 43% to 65% of the walnut's total weight, depending on its size.

It has unique qualities since the walnut shell is robust and takes a very long time to dissolve [14]. A range of grits, from extra fine to extra course, can be produced by breaking them down and grinding them. Walnut shells have also been used as an abrasive for the preparation of cementitious surfaces, including shotcrete surfaces, masonry walls, and poured-in-place concrete floors and walls [15]. Reusing these wastes to make concrete is a secure method of disposing of them. The effects of employing different agricultural wastes in cement and concrete were investigated by the researchers [3].

In every Iraqi city, walnuts are used to make desserts and food supplements. Depending on the size of the walnut, the resulting waste from its shell can range from 43% to 65% of its entire weight, necessitating a significant amount of land for disposal [16]. Concrete production requires a substantial amount of aggregate, and as cities grow, so does the aggregate demand, whether it be fine or coarse, which could result in resource depletion and the need to find alternatives to produce a green-friendly concrete [17], [18]. It is possible to save resources and create more ecologically friendly building materials by substituting waste materials for natural aggregates in concrete [19], [20].

The use of walnut shells as aggregates has been the subject of numerous studies, although these investigations have always concentrated on their mechanical qualities. It is challenging to find a study that examines how the use of walnut shells as aggregates affects the morphology of failure, the load-deflection relationship, and the deformation of concrete under applied loads for structural members, such as beams. Three different quantities of walnut shells were used in this study to replace coarse aggregate: 5%, 10%, and 15%, besides a control mix without any substitution. The effect of this type of waste as coarse aggregate on the flexural and shear behavior of reinforced concrete beams has been investigated.

II. Materials and Methods

A. Materials

Ordinary cement was used in the present investigation, and its properties satisfy Iraqi standards No. 5/2019 [21]. Natural sand zone 2 was used to make concrete mixtures for the work. The results indicate that the tests are within the bounds of Iraqi Specification No. 45/1984 Zone 2 [22]. Crushed gravel with a maximum particle size of 10 mm was utilized. Tap water was used to mix and cure the concrete. The collected walnut shells (WS) had a specific gravity of 0.96 and a water absorption of 10%. For usage as coarse aggregate, the WSs have been crushed into peeling-off shapes that range in thickness from 0.86 to 1.35 mm and have a maximum size of 10 mm. The procedure for preparing walnut shells as coarse aggregate is illustrated in Figure 1. The materials that have been used are illustrated in Figure 2.

Fig. 1 Procedure for WSA preparing

Fig. 2 Materials that used in this work

B. Methods

Three 100 mm cubes were used for the compressive strength test, which was conducted using an ELE-Digital testing apparatus with a 2000 kN capacity. The specimen was constantly loaded until the compressive strength could not be determined at 28 days of age. Cubic specimens were used for the test under BS EN 12390-3:2009[23]. Eight beams were subjected to bending tests using a hydraulic jack with a 500 kN maximum capacity, as shown in Figure 3. Along the length of the beam, the load was added gradually in 5 kN increments, beginning at zero and continuing until structural failure. A Linear Variable Differential Transformer (LVDT) was placed in the middle of the slab to precisely measure the mid-span deflection that corresponded to each load increment. A two-point loading setup was used to evaluate the beam's flexural response. The hydraulic jack applied the load during testing, and a computer-based data gathering system continually collected the applied load data.

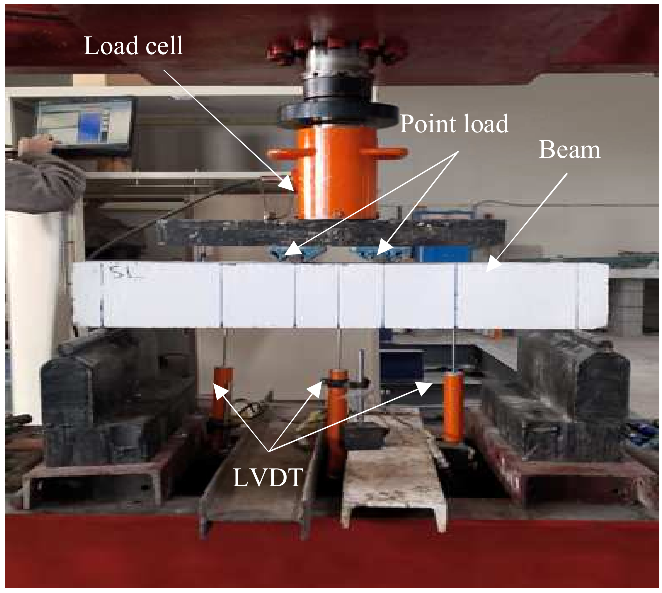

Fig. 3 Procedure for preparing of beams for testing

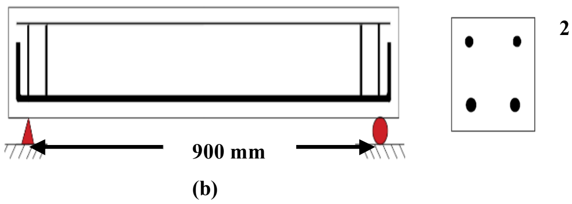

Fig. 4 Rienforced details (a) for flexural failure (b) for shear failure

III. Results and Discussion

A. Compressive strength

The results of compressive strength are illustrated in Figure 5. The leading causes of the decrease in compressive strength as the amount of walnut shell increases are the shells' poor mechanical strength, high porosity, and brittle cement paste binding. These properties diminish the concrete's resistance to compressive loads. In comparison to the control mix, the concrete's strength decreases significantly at 15% replacement because it becomes more porous and heterogeneous.

As the content of WSA in concrete increased, its compressive strength declined. WSA's increased porosity and lower internal strength when compared to natural coarse aggregates are the leading causes of this tendency. Additional voids are introduced by the walnut shells into the matrix, weakening its internal structure and decreasing its overall density. Furthermore, premature microcracking and failure under compressive loads may result from a weaker bond between WSA and the cement paste in the interfacial transition zone (ITZ). These results are in line with earlier research on the application of organic or lightweight aggregates in structural concrete [24], [25].

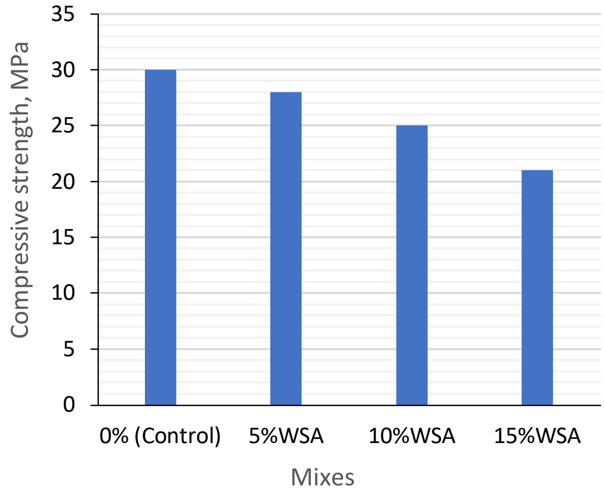

Fig. 5 Compressive strength vs. WSA%

B. *Load–Deflection Behavior for Tested Beam*

To investigate the effect of walnut shells as coarse aggregate on the behavior of reinforced beams, two groups of four beams were cast, each containing 0, 5, 10, and 15% walnut shells. The first group was designed for flexural failure, while the second set was free of stirrups. This allowed for further investigation of the effect of walnut shells on shear strength, and no previous studies were found on the impact of WSA on the shear behavior of beams.

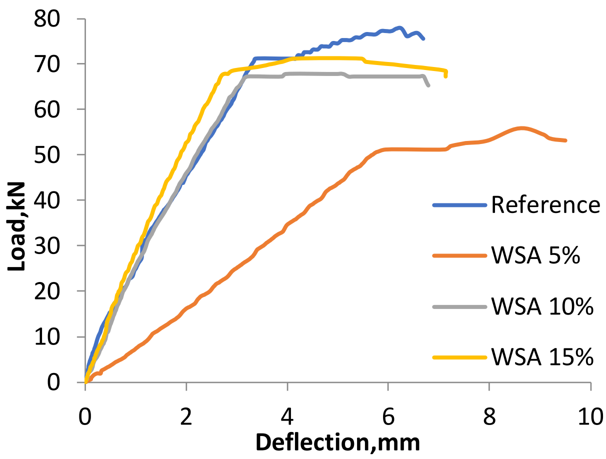

Fig. 6 Load - deflection vs. WSA% in flexural

Figure 6 shows the results of load-deflection for the first group, and Table 1 summarizes the results under two-point load. While all mixes with WSA showed lower flexural strength than the reference mix, there was an unexpected increase in flexural strength at 15% WSA content compared to 5% and 10%. This non-linear behavior can be explained by the improved distribution and interaction of WSA particles within the concrete matrix at higher contents, which enhances energy absorption and crack bridging under flexural loads. Studies looking into the content of lightweight aggregate (LWA) in concrete have also shown similar non-linear trends, with moderate inclusion levels improving mechanical performance through improved aggregate-matrix bonding and stress redistribution mechanisms [26], [27].

TABLE I
SUMMARIZED OF TESTED BEAM RESULTS

Group	Beams	*Ultimate load (kN)*	Change %	Maximum deflection (mm)	Change %
1	Reference	78.59	-	6.69	-
	WSA5%	55.28	-29.66	10.20	+52.47
	WSA10%	67.93	-13.56	6.97	+4.19
	WSA15%	71.26	-9.33	7.17	+7.17
2	Reference	62.60	-	3.48	-
	WSA5%	57.94	-7.44	4.39	+26.15
	WSA10%	53.95	-13.82	4.26	+22.41
	WSA15%	50.62	-19.14	4.48	+28.74

Additionally, because of enhanced stress transmission and fracture arrest processes, lightweight aggregates at low content levels might result in improved interfacial bonding and toughness by encouraging a more effective internal microstructure; a particular threshold of lightweight aggregate content may improve mechanical performance [27], [28]. Figure 7 shows the results of load-deflection for the second group, in which the beams were designed to fail by shear stress through the elimination of stirrups. All mixes with WSA showed lower flexural strength than the reference mix, and the shear strength decreased with the increase in WSA content. Due to their more ductile nature and ability to redistribute stress through controlled cracking, lightweight or organic aggregates, such as walnut shells, may help form a beneficial microcracking pattern in flexure, allowing the concrete to dissipate energy and delay failure [27]. Nevertheless, under shear loading, the same aggregates may decrease interfacial friction and overall bond strength, which could result in early shear failure because of weakened aggregate cohesion and interlock within the concrete matrix [29].

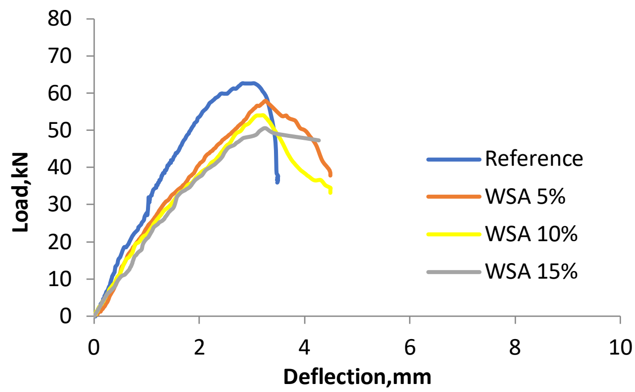

Fig. 7 Load-deflection vs. WSA% in shear

C. *Stiffness of Tested Beam*

The stiffness of beams was calculated using the following equation: Stiffness = crack load (Pcr)/related deflection (Δcr) The results were listed in Table 2.

Figure 8 illustrates the stiffness of Group 1. According to these results, the use of WSA as a partial substitute for natural coarse aggregate had a significant impact on the mechanical performance of reinforced concrete beams. The reference beam in Group 1 had a breaking load of 15 kN and a stiffness of 25.00 kN/mm. Since walnut shells are weaker and more deformable than traditional aggregates, adding 5% WSA resulted in a notable reduction in stiffness to 6.84 kN/mm (a 72.6% decrease). Nevertheless, a partial recovery of stiffness to 23.81 kN/mm and 21.21 kN/mm was achieved by raising the WSA content to 10% and 15%, respectively.

TABLE II
CALCULATION OF THE STIFFNESS OF TESTED BEAM RESULTS

Group	Beams	P_{cr} (kN)	Δ_{cr} (mm)	Stiffness	Change %
1	Reference	15	0.60	25.00	-
	WSA5%	13	1.90	6.84	-72.6%
	WSA10%	15	0.63	23.81	-4.8%
	WSA15%	14	0.66	21.21	-15.2%
2	Reference	16	0.40	40.00	-
	WSA5%	15	0.45	33.33	-16.7
	WSA10%	14	0.50	28.00	-30.0
	WSA15%	14	0.58	24.14	-39.6

Group 2 showed a similar pattern as shown in Figure 9, with the reference beam's stiffness of 40.00 kN/mm gradually declining as the WSA content increased. These results are consistent with earlier research, which shows that although adding WSA lowers the density of concrete, it may also result in a reduction in mechanical properties because the organic aggregate becomes less stiff and strong [13], [30].

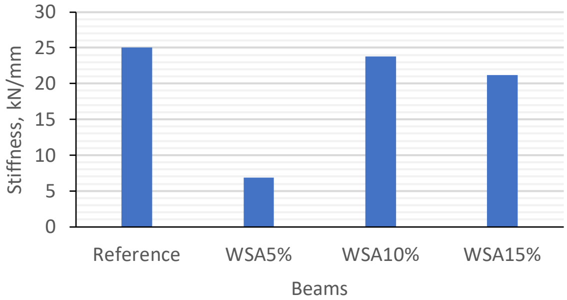

Fig. 8 Stiffness vs. WSA% for Group 1

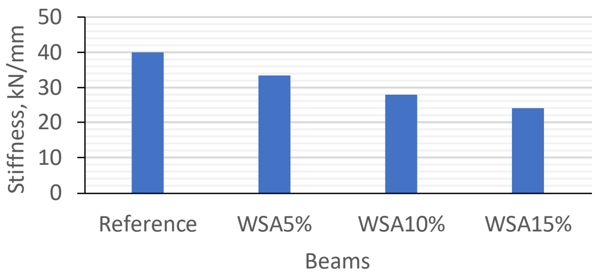

Fig. 9 Stiffness vs. WSA% for Group 2

D. Ductility of Tested Beam

A critical metric for assessing a structure's capacity to undergo plastic deformation before failure is ductility, which is defined as the ratio of the ultimate deflection to the yield deflection. In general, higher ductility values indicate better post-yield performance and energy absorption, which is crucial for structural parts subjected to dynamic or seismic stresses. The ductility of beams was calculated using the following equation:

Ductility = maximum recorded deflection (Δu)/yield deflection (Δy)

The results were listed in Table 3, according to these results WSA resulted in a discernible improvement in ductility in both beam groups.

TABLE III
CALCULATION OF DUCTILITY OF TESTED BEAM RESULTS

Group	Beams	Δ_u (mm)	Δ_y (mm)	Ductility	Change %
1	Reference	6.69	2.31	2.90	-
	WSA5%	10.2	1.62	6.30	+117.24
	WSA10%	6.97	1.47	4.74	+63.45
	WSA15%	7.17	1.64	4.37	+50.69
2	Reference	3.48	1.33	2.62	-
	WSA5%	4.39	1.44	3.05	+16.41
	WSA10%	4.26	1.30	3.28	+25.19
	WSA15%	4.48	1.44	3.11	+18.70

Figure 10 illustrates the ductility of Group 1. The reference beam in Group 1 had a ductility of 2.90. The ductility more than doubled to 6.30 with 5% WSA, a 117.24% increase. Ductility values of 4.74 and 4.37 at 10% and 15% WSA were noted; these values were still noticeably greater than the control. This implies that walnut shells may have a higher deformation capacity because of their greater microcracking and delayed ultimate failure, which is caused by their lower stiffness and more flexible nature.

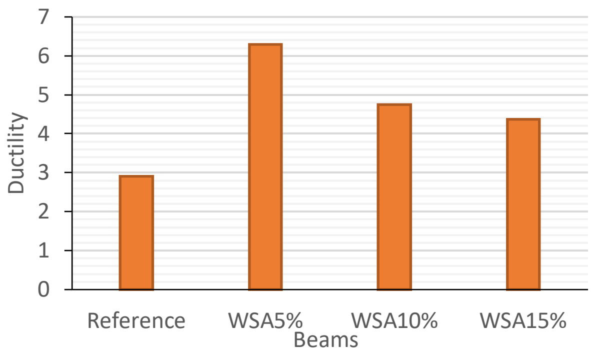

Fig. 10 Ductility vs. WSA% for Group 1

Group 2 experienced a milder increase in ductility, as shown in Figure 11. The ductility of the reference beam was 2.62, but the ductility of the beams with 5%, 10%, and 15% WSA increased by 16.41%, 25.19%, and 18.70%, respectively. This group's increased ductility lends more credence to the notion that WSA enhances structural resilience.

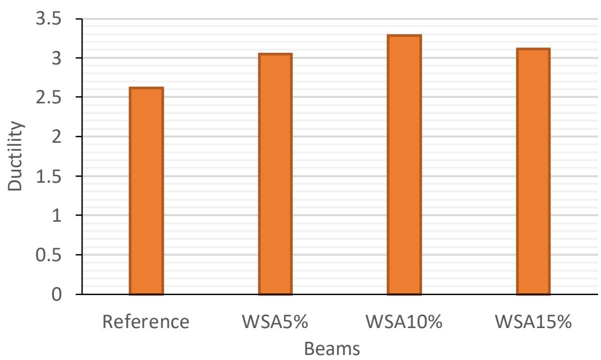

Fig. 11 Ductility vs. WSA% for Group 2

These results are consistent with previous research [13], [30], which found that adding lightweight organic materials, such as walnut shells, to concrete mixtures can enhance energy dissipation capacity, reduce brittleness, and promote widespread cracking. But too many replacements could weaken the structure as a whole; therefore, structural applications need careful optimization.

E. Toughness of Tested Beam

The ability of a material to absorb energy and undergo plastic deformation before failing is referred to as toughness. It shows the area under the load-deflection curve, see Table 4. A greater energy absorption capacity is indicated by higher toughness ratings, which is especially useful in structural applications susceptible to fatigue, seismic, or impact stress.

TABLE IV
CALCULATION OF THE TOUGHNESS OF TESTED BEAM RESULTS

Group	Beams	Toughness	Change %
1	Reference	262.76	–
	WSA5%	281.93	+7.3%
	WSA10%	236.63	-10.0%
	WSA15%	255.27	-2.8%
2	Reference	108.96	–
	WSA5%	127.15	+16.7%
	WSA10%	114.78	+5.4%
	WSA15%	113.36	+4.0%

The toughness of the reference beam in Group 1 was 262.76 N·mm, as shown in Figure 12. Toughness improved by 7.3% to 281.93 with 5% WSA replacement, indicating that a small amount of WSA may improve energy absorption, most likely as a result of better crack bridging and distribution. Toughness, however, dropped to 236.63 and 255.27 N·mm with greater WSA concentrations (10% and 15%), indicating 10.0% and 2.8% decreases, respectively. This suggests that while a small quantity of walnut shell can have a good impact on energy dissipation, too much replacement could weaken the matrix since the organic material's rigidity and bonding strength would be reduced.

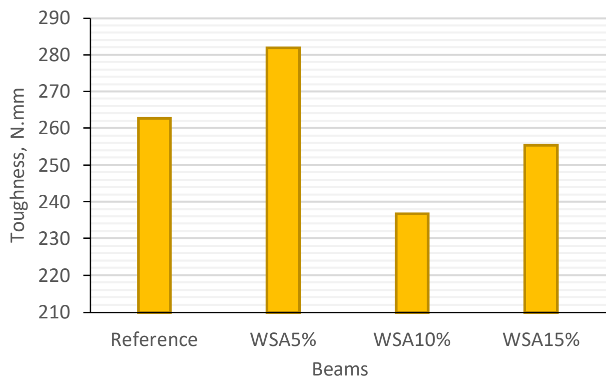

Fig. 12 Toughness vs. WSA% for Group 1

Figure 13 illustrates that the reference beam in Group 2 has a hardness of 108.96. Toughness increased to 127.15 (+16.7%), 114.78 (+5.4%), and 113.36 (+4.0%) when the coarse aggregate was replaced with 5%, 10%, and 15% WSA, respectively. These modest gains suggest that WSA may help beams with various designs exhibit improved post-cracking behavior and resistance to sudden failure. These patterns are consistent with earlier research [6], [13], [30], which showed that adding lightweight or organic aggregates enhanced ductility and energy dissipation under stress. Optimizing the replacement level to strike a balance between tough improvements and possible strength losses is necessary for effectiveness, though.

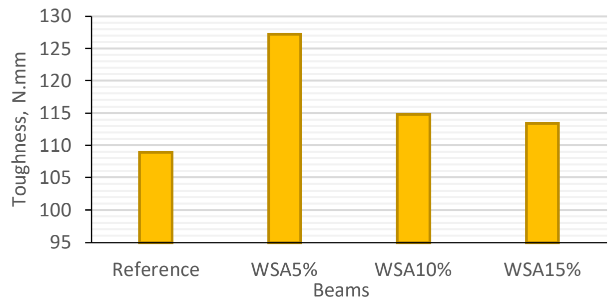

Fig. 13 Toughness vs. WSA% for Group 2

F. Crack width and Mode of Failure for Tested Beams

An essential factor in the failure characteristics of concrete beams was the partial substitution of walnut shell material for coarse aggregate. According to experimental results, the failure mode remained the same for both WSA mixes: flexural failure in the flexure group and shear failure in the shear group, but the width and severity of cracks significantly increased as the WSA content rose, as shown in Table 5, Figures 14 and 15.

TABLE V
CRACKS WIDTH AND MODE OF FAILURE OF TESTED BEAM

Group	Beam	Maximum crack width (mm)	Failure mode
1	Reference	3.0	**Flexure**
	5%WSA	3.0	**Flexure**
	10%WSA	3.5	**Flexure**
	15%WSA	4.0	**Flexure**
2	Reference	4.5	**Shear**
	5%WSA	5.0	**Shear**
	10%WSA	5.6	**Shear**
	15%WSA	5.8	**Shear**

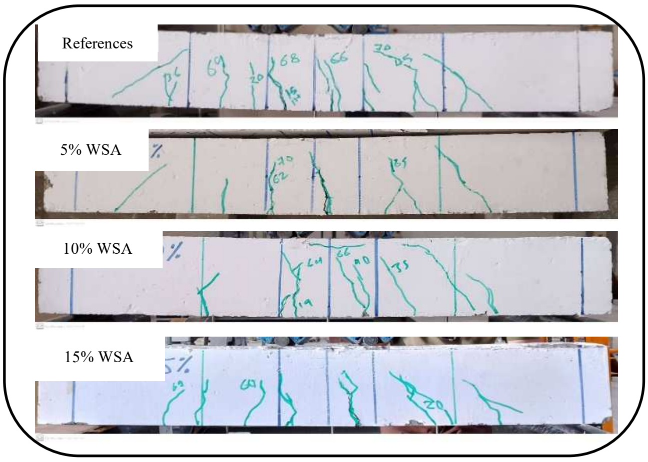

Fig. 14 Crack pattern and shape of failure for beams in Group 1

The highest fracture width in group 1 grew from 3.0 mm in the control beam (0% WSA) to 4.0 mm at 15% WSA replacement. Likewise, the maximum crack width in the shear group 2 increased from 4.5 mm (0% WSA) to 5.8 mm (15% WSA). This pattern implies that adding more WSA to concrete decreases its stiffness and resistance to cracking, maybe as a result of the walnut shell particles' reduced density and strength when compared to traditional coarse aggregates. These findings are consistent with other research, which shows that using lightweight or organic waste aggregates may cause cracks to spread more quickly and structural components to perform worse mechanically [6], [31].

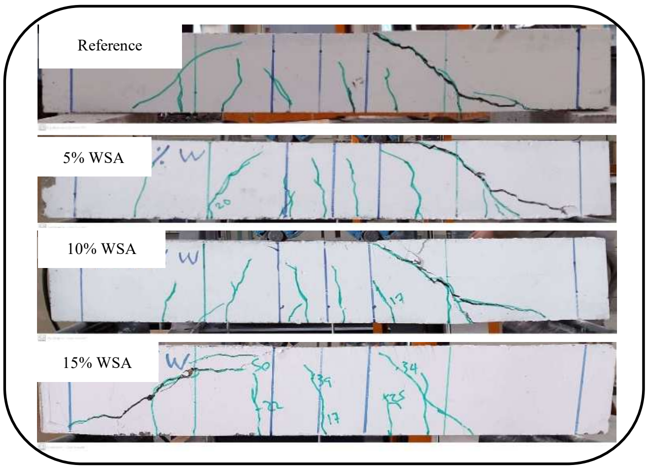

Fig. 15 Crack pattern and shape of failure for beams in Group 2

Notwithstanding these restrictions, beams with up to 5% WSA showed failure modes and fractured behavior similar to those of the control beams, suggesting that low-level substitution can be structurally feasible. Beyond 10%, however, more noticeable cracking and deformation were caused by the decreased modulus of elasticity and bond strength [13]. These results align with other studies on recycled aggregate concrete, which have also found that residual materials on aggregate surfaces and poorer interfacial transition zones lead to wider cracks and decreased shear capacity [32].

IV. Conclusion

The mechanical performance of reinforced concrete beams with walnut shell aggregate substituted at 5%, 10%, and 15% replacement levels for natural coarse aggregate was examined in this study. The experimental findings allow for the following deductions to be made. As the WSA concentration increased, a progressive decrease in compressive strength was noted. At 5%, 10%, and 15% WSA, the strength decreased from 30 MPa (control) to 28, 25, and 21 MPa, respectively. WSA is feasible for several structural and non-structural applications because, in spite of the reductions, sufficient strength was maintained at reduced replacement levels.

In comparison to the control specimens, the initial stiffness of the beams was generally decreased by the addition of WSA. Because of the walnut shells' inferior bonding qualities and lower elastic modulus, Group 1 showed the biggest loss at 5% WSA (-72.6%). The stiffness did, however, partially recover with 10% and 15% replacement, indicating a balance between internal structure compatibility and aggregate deformability.

When compared to their respective references, the ductility of all WSA-modified beams was enhanced. At 5% WSA (+117.24%), Group 1 showed the largest improvement in ductility, indicating improved post-yield deformation capacity and energy absorption. The walnut shell particles' flexibility and energy-dissipating properties are probably what caused this improvement.

The outcomes for each group's toughness differed. Toughness in Group 1 dropped as replacement levels increased, but it peaked at 5% WSA (+7.3%). Group 2, on the other hand, consistently improved toughness at all WSA levels, reaching +16.7% at 5% WSA. This implies that, in some circumstances, walnut shells may enhance the body's ability to absorb energy, particularly when used in the right amounts. However, at appropriate replacement levels (about 5–10%), WSA can improve toughness and ductility without appreciably sacrificing stiffness when used as a partial coarse aggregate replacement. These results lend credence to WSA's potential as a lightweight and sustainable substitute for aggregate in structural concrete applications, particularly those that require improved energy dissipation and deformability.

The experimental findings show that there is a discernible increase in crack width when the replacement level of WSA is raised. In comparison to control beams, beams with a higher WSA concentration showed earlier fracture start and broader diagonal shear cracks. This behavior is explained by WSA's reduced aggregate interlock, increased porosity, and decreased stiffness, which erode the internal bond and strain distribution.

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