# Experimental and environmental investigations of the impacts of wood sawdust on the performance of reinforced concrete composite beams

Ali A. Abdulhameed [a,*], Mahir M. Hason [b], Amjad Ali K. Sharba [c], Ammar N. Hanoon [a], Mugahed Amran [d,e], Hassan M. Magbool [f], Yaser Gamil [g,h,**]

[a] Department of Reconstruction and Projects, University of Baghdad, Baghdad 10071, Iraq
[b] Disaster Information Management Centre, Ministry of Science and Technology, Baghdad 10071, Iraq
[c] Department of Civil Engineering, Mustansiriya University, Baghdad, Iraq
[d] Department of Civil Engineering, College of Engineering, Prince Sattam Bin Abdulaziz University, 11942 Alkharj, Saudi Arabia
[e] Department of Civil Engineering, Faculty of Engineering and IT, Amran University, 9677 Amran, Yemen
[f] Civil Engineering Department, College of Engineering, Jazan University, Jazan, Saudi Arabia
[g] Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology, Sweden
[h] Department of Civil Engineering, School of Engineering, Monash University Malaysia, Jalan Lagoon Selatan, 47500 Bandar Sunway, Selangor, Malaysia

## A B S T R A C T

The majority of sawdust is produced by various lumber industries located all over the world. It has been established that using recycled materials to replace some of the fine aggregates is a viable solution. Most researchers focused on the durability aspect of wood sawdust concrete, while less information is available on its structural performance. Therefore, this article aimed to investigate the performance of reinforced concrete beams fabricated from concrete with a partially replaced fine aggregate (FA) by wood sawdust (WS) in the range of 5–45 % (by weight). Six beams underwent 4-point bending tests till collapse. The beams' slump, density, compressive strength, cracking and failure mode, energy absorption, and economic and environmental aspects were studied. The findings showed that the failure region of sawdust concrete was more significant than the reference samples. Despite the compressive strength of the concrete containing different ratios of sawdust being reduced by about 7–30 %, the target compressive strength still has a limit of low to normal concrete grade. The results show that the increase in sawdust percentages decreased the acquired absorbed energy of the subjected load to reach failure. A cost reduction of 9 % and a cost index of 61 % is achieved using wooden sawdust-based concrete. By substituting sawdust for fine aggregate, the sustainability of sawdust concrete in terms of cost and environmental advantages may be improved. In addition, it is well-known that harnessing the transformative potential of industrial waste in concrete production not only minimizes landfill usage, but also promotes resource efficiency, reduces carbon emissions, and advances the circular economy, propelling designers, engineering and builders towards a greener and more sustainable future in the construction industry. According to the test findings, wood sawdust may be utilized to produce normal and low-strength structural concrete.

* Corresponding author.
** Corresponding author at: Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology, Sweden
*E-mail addresses:* aliadel@uobaghdad.edu.iq (A.A. Abdulhameed), m.amran@psau.edu.sa (M. Amran), yaser.gamil@ltu.se (Y. Gamil).

## 1. Introduction

Both reinforced and prestressed concretes have been constructed with structural Lightweight Aggregate Concrete (LWAC). The use of LWAC often leads to overall cost savings of 10–20 % compared to normal concrete. Additionally, the reduced density allows for smaller structural element sections [1,2]. The aggregate (fines and coarse) is an essential component of concrete mixes. Due to urbanization and industrialization, total consumption has risen quickly over the past few decades. Also, there are fewer aggregate sources available locally, the price of aggregates is somehow kept rising. Using treated and untreated industrial by-products, household garbage, and others as raw materials in cement and concrete is currently popular worldwide These aid in recycling waste products and improve the environment by making them greener and cleaner [3–9].

Wood sawdust, Pumice, vermiculite, perlite, coal slag, sintered fly ash, rice husk, plastic bottles, oil palm fibre, etcetera, are a few lightweight aggregates used to produce lightweight aggregate concrete [10–12]. In addition to producing LWAC, these lightweight aggregates can also be recycled to create high-strength LWAC [13]. Compressive strength, or the maximal resistance of a concrete sample to the applied compressive stress, is one of the critical distinctions between lightweight and conventional concrete. When choosing aggregates for high, normal or low-strength concrete (about 10 MPa), manufacturers consider the aggregates' strength, ideal size, cement paste's bond with the aggregates, and surface characteristics [14].

After concrete, wood waste makes up the second-largest portion of construction and demolition trash. The debris is around 20–30 % of the overall building-related construction and demolition. Wood makes up around 10 % of all waste dumped in landfills each year. From 1990–2018, the total number of tones of wood generated, recycled, combusted with energy recovery, and discarded increased from 12,210 to 19,090, 130 to 3100, 2080 to 2840, and 10,000 to 12,150, respectively [15]. The waste product produced by the wood-based industry is called sawdust. It develops as small, uneven wood chips or small wood rubbish due to the slicing of timber logs into various sizes. Saw the types of wood influence dust dimensions and saw tooth sizes. Around the world, several research projects are being conducted on using waste materials to reduce environmental concerns while also expediting the present disposal of trash and recycling procedures due to their cost. According to published research, wood sawdust (*WS*), wood chippings, or wood shavings could be utilized to create lightweight concrete [16]. Large amounts of sawdust are produced as industrial waste and must be disposed of carefully. The timber industry all around the world produces the majority of the world's sawdust. Three million tons of sawdust are produced in the USA annually, most of which are dumped in landfills [17]. Disposing of Sawdust in the open area may harm human health. In Iraq and most developing countries, the difficulties contribute to pollution and other environmental challenges once these disposals are burned off. Hence, the proper use of sawdust continues to be difficult and will endanger the ecosystem and environment.

According to recent studies, wood sawdust is used as a Pozzolana in concrete as a partial replacement for cement or aggregate [16, 18,19]. It was found that replacing fine aggregate with wood sawdust in concrete resulted in a substantial decrease in the workability and the hardened density with increasing the percentage of wood sawdust replacement [16,20]. Numerous researchers reported similar results [21–23]. Besides, replacing sand with dry fine saw dust reduces the thermal conductivity of conventional and LWC, which in turn lowers carbon dioxide emissions [24]. It is established that using untreated wood increases concrete's ability to insulate when grading between (0.1–8) mm, decreasing the compressive strength [25]. A reliable declination in short-term mechanical properties of concrete made with wood sawdust was observed [22,24]. It has been demonstrated that replacing sand in concrete with sawdust ash is effective [26]. Scholars investigated the effectiveness of adding sawdust to clay bricks to lessen shrinkage and suggested utilizing sawdust to create lightweight brick, which complies with the code's requirements [27]. Another researcher conducted an experimental investigation on wood sawdust concrete blocks and obtained a compressive strength higher than 12 MPa [28]. It was determined that 5 % sawdust replacement for sand resulted in concrete with mechanical characteristics that are equivalent to the reference conventional mixture [16].

For this reason, thorough research is required to support further the usage of sawdust as a substitute for aggregate or sand. The inclusion of sawdust negatively impacts the mechanical properties of the concrete, although previous research has shown that it has much potential as a substitute aggregate for medium to low-strength concrete purposes. For structural and non-structural purposes, Japan has previously approved using recycled concrete with compressive strengths ranging from 18 *MPa* to 45 *MPa* [29]. Low-strength non-structural concrete produced from recycled concrete and industrial waste was permitted in numerous countries, including Canada, Brazil, the UK, and Hong Kong. Based on the ACI-229R, concrete materials with low strength, such as wood sawdust concrete, might have a strength as low as 10 MPa, which is appropriate as an alternative substantial for many structural and non-structural utilizations [29,30]. There has been limited research on the structural assessment of RC beams containing various ratios of sawdust waste. To fill this gap, this study is concerned with the behavior of RC beams (shear performance) containing different waste wood sawdust ratios. This research is part of an ongoing investigation into the use of waste wood in construction. It is hoped that the detailed specifications and optimal sawdust combination offered by this paper will assist manufacturers in creating several grading of sawdust concrete.

Although extensive experimental studies have been conducted to examine the efficiency of sawdust concrete cubes and cylinders, rare studies have been reported related to the study of the performance of RC beams under the impact of structural loads for both structural and non-structural utilizations [11]. As more environmentally friendly solutions are needed for global environmental challenges, sawdust use is growing. Because sawdust concrete is far less dense than traditional aggregate concrete, using it lessens the structure's dead weight, reducing the need for foundation applications [12]. The creative use of sawdust as a construction material also can divert a significant amount of industrial waste from landfills because it is a waste item with no other practical function or resale value. The usage of sawdust concrete may also have advantageous thermal and soundproofing advantages.

It is well known that the ultimate shear strength of a beam is usually influenced by many factors: reinforcement ratio, beam size, (a/d) ratio, the tensile strength of concrete, and particle types of the aggregate [29]. Consequently, it can be expected that this research

will fill in the information gap about how sawdust affects the characteristics of concrete and, in the end, assist manufacturers in expanding the use of sawdust concrete as an insulating material for commercial usage. Moreover, in this research, the fine aggregate was replaced by various ratios of wood sawdust to discover the impact of this material on the shear strength, load capacity, and failure mode. Therefore, this paper aimed to investigate the structural performance, energy absorption, crack configurations, failure modes, and cost and environmental impacts of concrete beams with different WS contents under structural load. The experimental information reported in this paper helps to understand the structural performance and strength of concrete beams incorporating *WSs*.

## 2. Materials and methods

### 2.1. Material properties and preparation

Local Iraqi ordinary Portland cement (type CEM-I-42.5*R*), which follows the Iraqi requirement (IQS 5/1984), was used in this experiment. The chemical composition of the used cement is shown in Table 1. The concrete mixture design was based on ACI Standard 211.1 [31]. The maximum size of crushed coarse aggregate, w/c ratio, and slump measurement was 20 mm, 0.52, and (27−83) mm, respectively. Furthermore, wood sawdust [WS] was used in this study as a partial replacement of the fine aggregate (FA) (Fig. 1). The WS was obtained from the home furniture manufacturing company which is a local wood manufacturing company located in Baghdad, Iraq. The particle size distribution of the wood sawdust was conducted by the vibrating screen method according to EN17827−2−2016. The particle size distribution for the sand and sawdust utilized in this investigation is shown in Fig. 2., indicating that fine aggregate particle size is comparatively coarser than wood sawdust. Table 2 presents the aggregate properties utilized in the study.

Tap water was used for mixing concrete constituents, and the water cement ratio (w/c) was (0.4) which kept constant for all mixes as presented in Table 3. Sand and sawdust were physically combined to create a consistent mixture. Then, the sand and coarse aggregates were added to the mixing apparatus. In the end, the mixture was combined with cement and water. Concrete was mixed using a typical mixture machine (Fig. 3). A slump test was conducted with the freshly mixed concrete. Three samples of 150 mm × 300 mm cylinder moulds were filled for each batch once the mixing procedure was complete, and they were then placed in a saturated curing container and kept there for 28 days until the day of testing (Fig. 4). The average reading of compressive strength was adopted. Concrete was mixed based on five replacement percentages of WS (5, 15, 25, 35, and 45) % by volume of FA. The beam samples that included different ratios of WS were notated as WSCB-05, WSCB-15, WSCB-25, WSCB-35 WSCB-45, noting that WSCB-00 represents the control/reference beam without WS. More details about beam designation and concrete mixes are illustrated in Fig. 5 and Table 3, respectively.

### 2.2. Test setup, geometry, instrumentation and procedures

Six identical rectangular beams were used in this experiment. Each beam specimen has the same longitudinal, transverse reinforcements and size geometry of 1100 × 200 × 150 mm. The tension reinforcements consisted of two 12-mm-diameter bars, and the reinforcements in the compressive zone were two 6-mm-diameter bars running only along the shear regions (Fig. 6). To be sure that the flexural strength of the reinforced concrete beams is significantly higher than the predicted experimental shear failure, the beams were fabricated to undergo shear failure. The steel reinforcement ratio was calculated according to Building Code Requirements for Structural Concrete (ACI 318 M-19), chapter 9, section 9.6 (Reinforcement limits). A flexural steel ratio of 1% was adopted. The target compressive strength of the concrete mixture for all batches was 30 MPa. The mechanical characteristics of the reinforcement bar are illustrated in Table 4.

The beams were cast according to the specified proportions of the testing. After the frameworks were removed and the necessary curing was provided, the beams were painted with white color to provide clear vision for deflection, cracks, and failures, as shown in Fig. 7. With a span length of 1100 mm, the beams were simply supported and tested under two-point loads that increased monastically. The fine aggregates' various replacement ratios of sawdust (5 %, 15 %, 25 %, 35 %, and 45 %) were used to study the impact of shear

**Table 1**
Chemical and physical properties of cement.

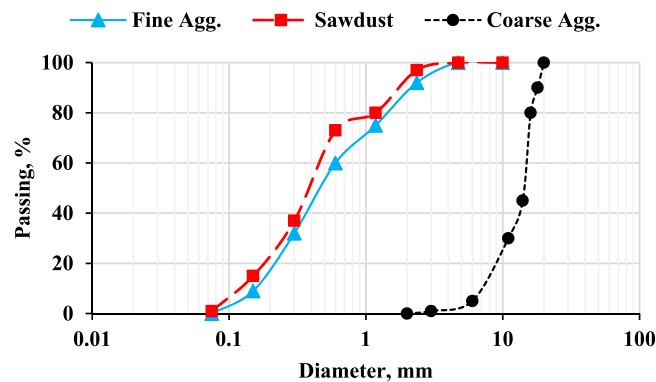| Components | % by weight | Iraqi limitation (IQS-5/1984) |
|---|---|---|
| Chemical properties | | |
| $CaO$ | 61.52 | - |
| $SiO_2$ | 21.67 | - |
| $AL_2O_3$ | 5.33 | - |
| $Fe_2O_3$ | 3.31 | 5.0 |
| $MgO$ | 2.97 | 2.8 |
| $SO_3$ | 2.45 | 4.0 |
| I.R. | 0.91 | (0.66–1.02) |
| L.S.F. | 0.86 | |
| Physical properties | | |
| L.O.I | 3.41 | 1.5 |
| Specific surface area ($m^2/kg$) | 430 | 230 (lower limit) |
| Unit weight ($kg/m_3$) | 3150 | |
| Color | Gray | |

Fig. 1. Wood sawdust material utilized.



Fig. 2. Distribution of aggregate particle sizes used in concrete mixes, including sawdust, coarse aggregates, and fine aggregates.

**Table 2**
Aggregate properties.

| Type | Specific gravity | Density ($kg/m^3$) | Fineness Modulus | Absorption, % | Water content, % |
|------|------------------|--------------------|------------------|---------------|------------------|
| CA | 2.7 | 1650 | 6.5 | 0.5 | 3 |
| FA | 2.65 | 1688 | 2.64 | 3 | 5 |
| WS | 0.45 | 180 | 1.8 | - | - |

**Table 3**
Variable concrete mixture proportions.

| Designation | Fine aggregate (kg/m³) | Sawdust | | Coarse aggregate (kg/m³) | Cement (kg/m³) | Water (kg/m³) | w/c ratio |
|-------------|------------------------|---------|---|--------------------------|----------------|---------------|-----------|
| | | Volume (%) | Weight (kg/m³) | | | | |
| WSCB-00 | 890 | 0 | 0 | 1080 | 356 | 141 | 0.4 |
| WSCB-05 | 846 | 5 | 45 | 1080 | 356 | 141 | 0.4 |
| WSCB-15 | 757 | 15 | 134 | 1080 | 356 | 141 | 0.4 |
| WSCB-25 | 668 | 25 | 223 | 1080 | 356 | 141 | 0.4 |
| WSCB-35 | 579 | 35 | 312 | 1080 | 356 | 141 | 0.4 |
| WSCB-45 | 490 | 45 | 401 | 1080 | 356 | 141 | 0.4 |

load on the wood sawdust concrete.

A universal compressive machine with an electrical hydraulic system was utilized to conduct the testing. The machine has a loading capacity of 3000KN and comprised of four units: a Jack and trolley unit, pump unit, electrical control unit, and analog indicatore unit as shown in Fig. 8. Two gauges were installed under the central span of the specimen to determine the mid-span deflection. The beams were under monotonically increasing two-point loads. At a rate of 0.3 kN/s, the load was applied in a load-controlling manner. Every 5 kN of loading was halted in order to measure deflection, examine the crack width, and determine the locations of the cracks.

**Fig. 3.** Concrete mixer.
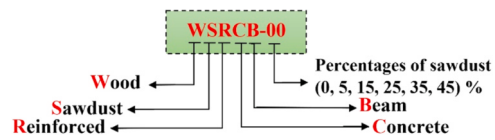


**Fig. 4.** Compressive strength test.



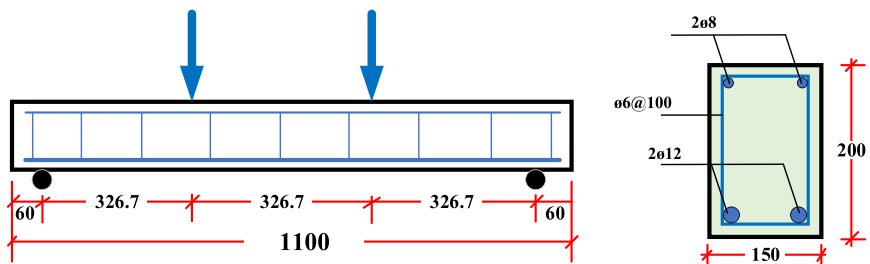**Fig. 5.** Beams nomenclature system.



**Fig. 6.** Beam geometry and reinforcement (all dimensions in mm).

**Table 4**
Reinforcement properties.

| Rebar, mm | Type | Elongation (%) | $F_y$ (MPa) | $F_u$ (MPa) |
|---|---|---|---|---|
| 6 | round | 30 | 450 | 480 |
| 8 | deformed | 24 | 410 | 588 |
| 12 | deformed | 20 | 620 | 725 |



**Fig. 7.** Specimens productions and preparation.

## 3. Results and discussions

In this study, six wood sawdust-reinforced concrete beams (WSCB) specimens, including a control beam that acted as a reference point for comparison were tested. The beams were identical in geometry and steel reinforcement but different in the replacement percentage of fine aggregate (FA) by wood sawdust (WS) (0 %, 5 %, 15 %, 25 %, 35 %, and 45 %). According to these variables, ultimate loads (Pu), cracking load (Pcr), deflection (δ), crack patterns, modes of failure, cost, and environmental impact are different from each beam to another.



(a)  Universal Testing Machine

(b)  Deflection gauges

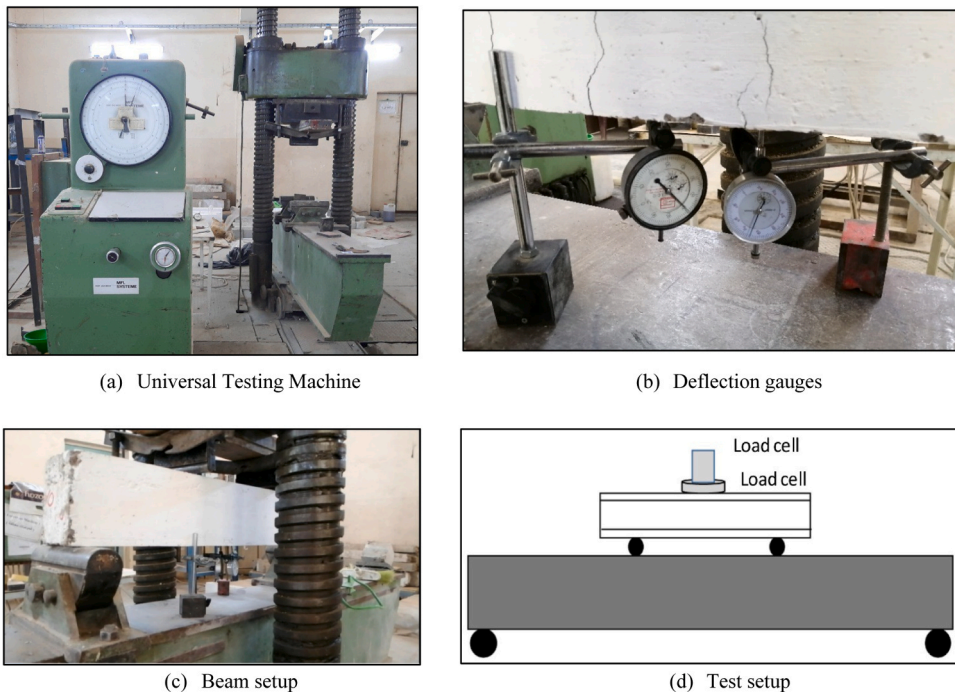(c)  Beam setup

(d)  Test setup

**Fig. 8.** Test instrumentation.

### 3.1. Fresh and hardened characteristics

The slump values of the prepared concrete as a function of the FA replacement levels for waste sawdust are presented in Table 5 and Fig. 9(a). The findings of the slump measurement demonstrated that the workability of the produced concretes decreased when sawdust replaced natural aggregate content. With a rise in the ratio of FA replacement from 0 % to 5 %, 15 %, 25 %, 35 %, and 45 %, the value of slump was reduced by 7 %, 13 %, 19 %, 30 % and 47 %, respectively. Typically, as the amount of sawdust in the mixes increased, the workability of the concrete decreased. However, the influence was more noticeable at greater sawdust concentrations (45 %). The specific surface area of the sawdust and the high water demand with a high amount of sawdust in the matrix impacted the concrete's workability. In a different sense, using waste sawdust as fine or even coarse aggregates effectively improved the concrete's texture by adding numerous uneven and extremely rough fine porous particles. As a result, it reduced the inter-particle friction that was preventing the flow of fresh concrete. The workability decreased as the amount of sawdust used to replace the fine aggregate increased for a fixed (w/c) ratio. For the decrease in the workability of concrete, including lightweight particles, several researchers have found trends of findings that are similar [29,32]. This issue could be resolved by utilizing a superplasticizer and overcoming the disadvantages associated with the decrease in workability in concrete mixtures produced by using sawdust waste as a partial replacement to fine aggregates which need further investigations.

The hardened density quantities of the constructed waste sawdust concrete used as partial FA replacement are also shown in Table 5 and Fig. 9(b). When the sawdust substance was raised from 0 % to 5 %, 15 %, 25 %, 35 %, and 45 %, the densities of the produced concretes were lowered by 5 %, 10 %, 21 %, 28 % and 41 %, consecutively. The combination with the lowest density (1402 $kg/m^3$) was comprised of 45 % sawdust. This is most likely because the porosity and low specific gravity of the sawdust significantly affected the densities of the designed concretes. The current result is comparable to concrete, including a significant amount of sawdust as an aggregate achieved by [32].

Furthermore, compressive strength is the most crucial factor when assessing the concrete's mechanical properties, designing new buildings, and the structure's capacity to withstand weathering conditions. Thus, Fig. 9(c) shows the effect of adding different amounts of WS ratios on the compressive strength of the sawdust concrete. With an increase in the dose of sawdust replacement from 0 % to 5 %, 15 %, 25 %, 35 %, and 45 %, the strength is dropped by 7 %, 12 %, 20 %, 26 % and 30 %, respectively. A comparable reduction was seen with the sawdust contents increasing in the concrete matrix. These outcomes harmonize with the earlier literature results [26,29, 32].

Besides, it was discovered that the maximum strength loss was decreased from 32.47 % to 22.85 % when the density was decreased from 2365 (kg/m³) to 1402 (kg/m³) (see Fig. 10) at 45 % sawdust addition at a 28-day age. As a result, four factors could undoubtedly address the overall decrease in $f'c$ caused by an increase in sawdust substance [14,32,33]: (1) Waste sawdust had a greater capacity to absorb water than the fine aggregate. However, the uneven water distribution in the concrete matrix may cause the chemical bonds between the constituent components to deteriorate, (2) the bond between the binder and the particles of sawdust was less than that of natural aggregates, which led to a decrease in the compressive strength of the concrete, (3) organic matter caused the aggregate-paste bindings to weaken and the porosity to rise, which impacted the $f'c$ of the concrete and (4) the lack of pozzolanic activity by the sawdust waste and the substitution of the more vital component for the weaker one both had a detrimental impact on the development of strength. To conclude, with a range of 7–30 %, the compressive strength decreases as the sawdust percentage rises. It is reported that the minimum compressive strength for light weight concrete and moderate-strength concrete are 17 MPa and (7−17) MPa [2]. As stated by ACI-229R, concrete materials with low strength might have strength down to 10 *MPa* [30]. Therefore, the compressive strength of wood sawdust concrete obtained in this study higher than the acceptable range mentioned in the literature. In terms of more confident statistical analysis, Table 6 illustrates the *ANOVA* analysis of the mixtures' compressive strength utilized in this study.

### 3.2. Relationship between deflection and monotonic load

The deflection of the tested beams against monotonic load for all experimental specimens are presented in Fig. 11. While comparing the behavior of the specimens using the wood sawdust waste, there was no discernible difference in terms of flexural stiffness; instead, it followed the same pattern for both control and sawdust samples of concrete. All beams respond similarly to modest applied loading before or after cracking. This control beam exhibits a more significant deflection at the ultimate load than the other beams manufactured using WS at the ultimate stage. According to the experimental findings, utilizing wood sawdust reduced the shear capacity

**Table 5**
Fresh and hardened properties of concrete mixtures.

| WS (%) | Slump (mm) | Hydration Period (days) | Density (kg/m³) | Sample | | | Average $fc$ (MPa) | StDev | CoV | 95% CI |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 | | | | |
| 0 | 83 | 28 | 2365 | 30.66 | 32.92 | 33.82 | 32.47 | 1.63 | 5.01 % | (31.23, 33.7) |
| 5 | 77 | | 2243 | 31.2 | 30.01 | 29.11 | 30.11 | 1.05 | 3.48 % | (28.87, 31.34) |
| 15 | 64 | | 2140 | 29.46 | 28.31 | 28.1 | 28.62 | 0.73 | 2.56 % | (27.39, 29.86) |
| 25 | 50 | | 1870 | 26.80 | 25.36 | 25.42 | 25.86 | 0.81 | 3.15 % | (24.63, 27.09) |
| 35 | 39 | | 1710 | 24.56 | 23.74 | 23.88 | 24.06 | 0.44 | 1.82 % | (22.83, 25.29) |
| 45 | 27 | | 1402 | 22.76 | 23.68 | 22.1 | 22.85 | 0.79 | 3.47 % | (21.61, 24.08) |
| | | | | Pooled *St Dev* = 0.98 | | | | | | |

**(a)** Slump



**(b)** Density



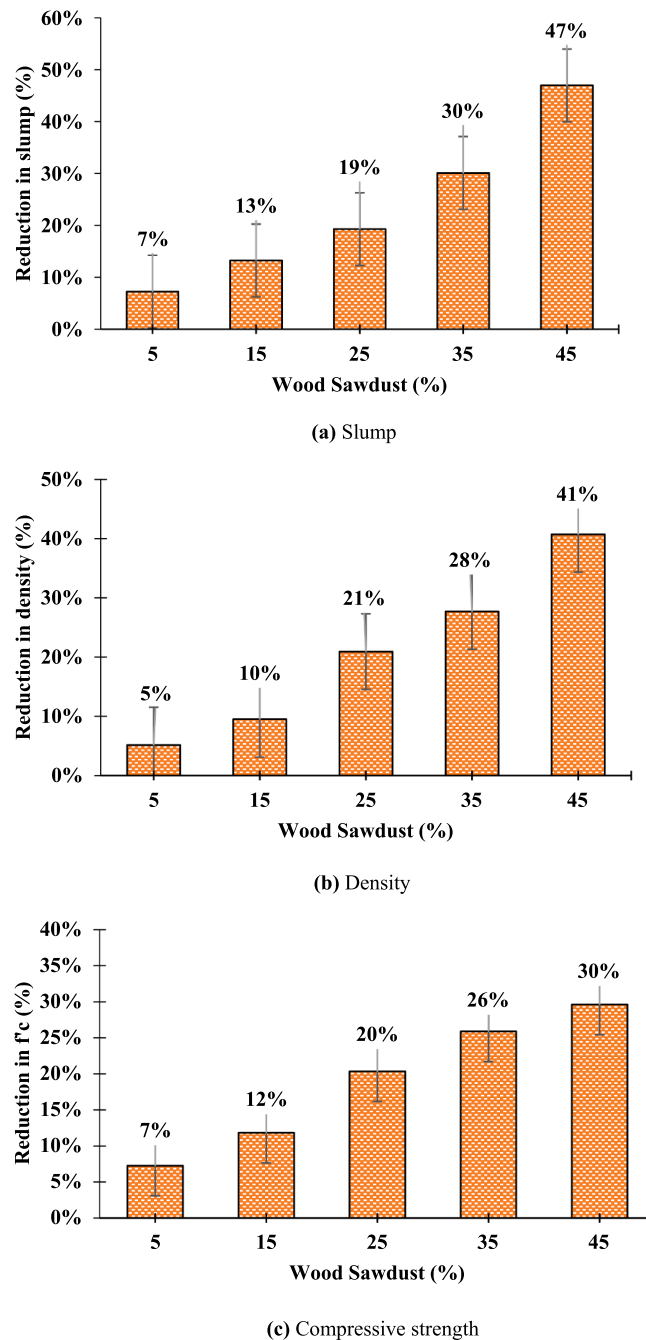**(c)** Compressive strength

**Fig. 9.** Reduction percentage in fresh and hardened properties relative to control specimen.

compared to using a control sample. As shown in Fig. 11, the *(P-δ)* graph begins with a high gradient and gradually flattens until the maximum moment region near the middle of the beams, where flexural cracking first appears. Once the transverse reinforcements start to give up, the curves continue to behave linearly, and it is clear that the control beam had somewhat more stiffness than the WS beams.

Nonetheless, the *(P-δ)* behaves in a curved path during the stage of the yielding load to the ultimate load. Following that, the resistance to the external load decreased gradually and smoothly in all of the tested beams, indicating a less ductile attitude of the beams. Due to the substitution of wood sawdust waste with fine aggregate, the behavior of the WS beams investigated in this work was more brittle.

The behavior of beams (WSCB-15, WSCB-25, WSCB-35, WSCB-45) shown in Fig. 11 failed in the shear span due to their brittleness compared to WSCB-00 and WSCB-05 beams. The beam with a small amount replacement of FA with WS (WSCB-05) has a comparable flexural stiffness characteristics. This is probably because the limited WS of 5 % of did not affect the RC beam's behavior. The
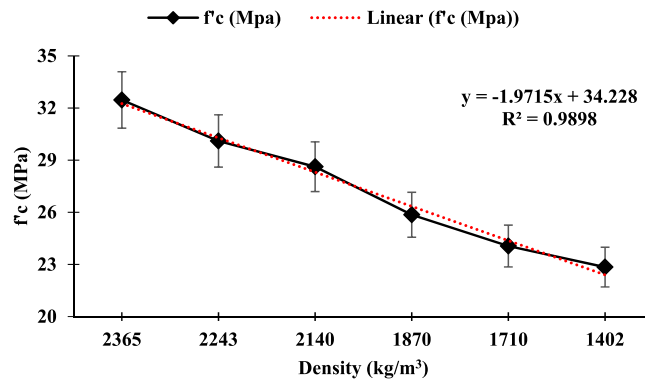
**Fig. 10.** Correlation between density and compressive strength.

**Table 6**
ANOVA for the compressive strength.

| Null hypothesis | All means are equal | | | | | | |
|---|---|---|---|---|---|---|---|
| Alternative hypothesis | Not all means are equal | | | | | | |
| Significance level | $\alpha = 0.05$ | | | | | | |
| Equal variances were assumed for the analysis. | | | | | | | |
| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
| Factor | 5 | 206.17 | 94.70 % | 206.17 | 41.2332 | 42.87 | 0 |
| Error | 12 | 11.54 | 5.30 % | 11.54 | 0.9619 | | |
| Total | 17 | 217.71 | 100 % | | | | |
| Model Summary | | | | | | | |
| S | $R^2$ | $R^2$ (adj) | PRESS | $R^2$ (pred) | | | |
| 0.980759 | 94.70 % | 92.49 % | 25.971 | 88.07 % | | | |
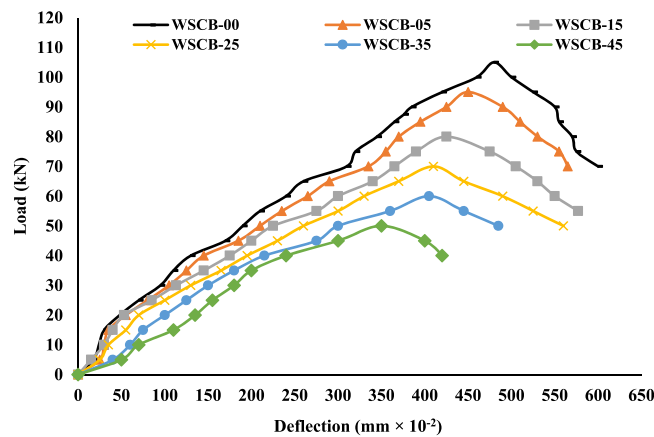


**Fig. 11.** Correlation between load and deflection.

experimental results of all tested beams, as listed in Table 7, show that the ultimate loads for WS beams are less resistant than the ultimate loads for control beams. Similarly, the deflection of WSCB beams is also less than that of the control beam due to the increase in brittleness of WSCB beams. The experimental test results presented that the maximum deflection at ultimate load for the control beam occurs when there is no attendance of WS, whereas the deflections started to decrease with the increase of WS percentage. The difference in deflection values is attributed to the difference in the equivalent compressive strength of each specimen, depending on the amount of replacement percentage of fine aggregates with wood sawdust. The deflection stops when the failure occurs, typically after a reduction of about 20 % in the ultimate strength or after reaching the ultimate strengths; the cracking becomes too much, leading to weakness and failure after about a 15–20 % reduction in strength; this is typical in concrete. Furthermore, the maximum and minimum deflections are about 4.6 mm and 3.0 mm for WSCB-00 and WSCB-45 beams, respectively, as shown in Fig. 11 and Table 7.

**Table 7**
Crack and ultimate loads details with corresponding deflections.

| Beam Designation | Load (*kN*) | | Deflection (*mm * 0.01*) | | (*Pcr/Pu*) (%) |
| --- | --- | --- | --- | --- | --- |
| | $P_{cr}$ | $Pu$ | at first crack | at ultimate load | |
| WSCB-00 (Control) | 70 | 100 | 310 | 460 | 70 |
| WSCB-05 | 65 | 95 | 290 | 450 | 68 |
| WSCB-15 | 50 | 80 | 225 | 425 | 63 |
| WSCB-25 | 40 | 70 | 195 | 410 | 57 |
| WSCB-35 | 25 | 55 | 125 | 360 | 45 |
| WSCB-45 | 20 | 50 | 135 | 300 | 40 |

*3.3. Cracking and failure criteria*

The initial bending cracking occurred sooner for the sawdust concrete specimens relative to the control sample, and the subsequent crack development and opening were apparently notable. This is obviously due to the existence of *WS*, which led to a lowering in the tensile strength of the concrete. During various percentages of the ultimate load ($P_u$), the shear cracks were first discernible relatively at the midpoints height of the experimented beam throughout the shear span (Fig. 12). Furthermore, the number, length, and thickness of the cracks grew as the load was increased, and the shear cracks moved upward in the direction of the monotonic load and to the support or a location close to the support. The transverse reinforcement along the shear span minimized the penetration of diagonal cracks into the compression zone and curbed their propagation, thereby enhancing the proportion of the shear force that the concrete compression zone could resist. The total diagonal cracks were gradually formed after the yielding of the stirrups. Observable variations in the cracking mode and arrangement were noticed due to the different replacement ratios of the fine aggregates with wood sawdust (5 %, 15 %, 25 %, 35 %, and 45 %) combined in the test beams. There is no discernible difference in the fracture width between the RC reference beam and the WSBC beams, as seen in Fig. 12. To conclude, the load-deflection response was approximately similar between the concrete beams with WS and was comparable to those of the control beam; however, the shape and propagation of the crack were different. Back forth to Fig. 12, the WSCB-05 and WSCB-15 samples exhibit narrower cracks compared to the control sample WSCB-00. Conversely, the WSCB-35 and WSCB-45 samples displayed wider cracks.

The six beams failed with the same traditional method of shear failure because the prominent diagonal cracks complied with the failure of concrete in the shear span zone, which is controlled by the failure of shear reinforcement and the regional bond of the tension reinforcement close to the support. Generally, the control beam exhibited higher tensile strength than the wood sawdust concrete
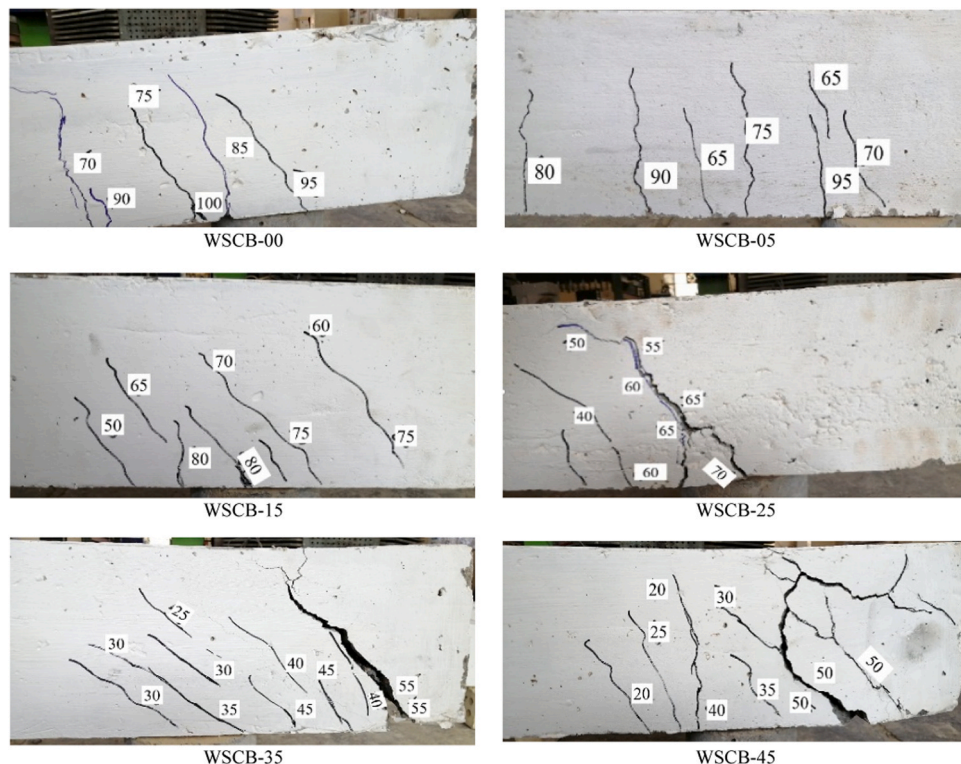


**Fig. 12.** Beam failures modes.

beams (WSCB). Fig. 13 and Fig. 14 report the reduction percentages in crack load and ultimate load compared to the control beam (WSCB-00) without WS. As shown by the experimental results, the shear capacity was decreased due to using different ratios of WS for sawdust concrete beams compared to the reference sample. The maximum reduction in crack load and ultimate load are observed in WSCB-45 beam. Furthermore, beam WSCB-00 (control beam with normal aggregate) can withstand the maximum load compared to other beams WSCB-05, WSCB-15, WSCB-25, WSCB-35, and WSCB-45, which are reduced by about 5 %, 20 %, 30 %, 45 %, and 50 %, respectively. The two beams with a high ratio of WS (WSCB-35 and WSCB-45) show a lower ultimate load, whereas the beams with lower WS ratios show the utmost load. Eventually, using a high WS percentage reduced the shear resistance (capacity).

### 3.4. Energy absorption

When a structural member is exposed to various loadings, energy absorption (EA) serves as a gauge of its structural system integrity. Dissipated energy during loading is the total energy throughout the elastic and plastic phases. It is commonly known that the idea of energy absorption is one technique to determine a structure's capacity to withstand loads [34–37]. Various methods have been deployed to calculate the EA of conventional and unconventional concrete beams. One effective method, the total energy absorption is equal to calculating the area under the curve, which represents the load-displacement curve (*P-δ*) (Eq. 1), which is following Simpson's rule criteria (Eq. 2) [4,38] as shown in Fig. 15. Accordingly, Fig. 16 shows the measured values and reduction percentages of EA for the teseted beams obtained from this study. The existence of waste wood material, as a partial volumetric replacement of fine aggregates, has reduced the total amount of energy absorption of the beams by 15 %, 23 %, 35 %, 53 %, and 70 % for the WS replacement of 5 %, 15 %, 25 %, 25 %, 35 %, and 45 %, respectively.

$$EA = \int_0^{\delta_{max}} P.d\delta \tag{1}$$

$$Area = \frac{(P_i + P_{i+1})(\delta_{i+1} - \delta_i)}{2} \tag{2}$$

### 3.5. Cost investigation and environmental impact

Suitable use of waste material such as wood sawdust in construction materials will noticeably protect the ecosystem and minimize the overall costs by lowering the usage of conventional resources and thus reducing carbon dioxide ($CO_2$) emissions. In this study, the suggested concrete mixtures' cost performance and environmental impact were assessed by calculating the values of the economy factor (cost index) and $CO_2$ emission, respectively. Table 8 shows the cost analysis of several concrete combinations created using various ratios of wood sawdust. In order to determine the ideal sawdust mix ratio, the cost index has been calculated by dividing the compressive strength (fc') for each concrete mixture by the cost of one cubic meter (1 m3) of components. In contrast to sawdust and water, the cost of cement, fine aggregate, and coarse aggregate are taken into account to calculate the total cost of one mixture. It should be emphasized that the price of sawdust won't have an impact on this cost estimate because it is a free resource received from a local factory and utilized as a better method than depositing it in landfills or utilizing it as burning fuel for cooking in rural regions. Table 8 shows that the percentage of utilized sawdust may be a reasonable limit compared to the reference concrete batch since all cost indices have a percentage of more than 60 %. Table 8 also shows a straight impact on the overall cost of aggregate-based concrete mixtures. Moreover, the price of FA was lowered from 7.81 to 7.42, 6.64, 5.86, 5.08, and 4.3 (USD per kg/m³) when the ratio of WS increased from 0 % to 5 %, 15 %, 25 %, 35 %, and 45 %, consecutively. It is demonstrated that sustainable concrete can be produced by using wood sawdust instead of fine aggregate.

Fig. 16 shows that using different ratios of WS in concrete mixtures reduces the total mixture cost. Using 5 %, 15 %, 25 %, 35 %, and 45 % of WS as a replacement of FA in mix design resulted in cost reduction of about 1 %, 3 %, 5 %, 7 %, and 9 %, respectively from the total cost of 1 m³ of concrete mixture following the local price of the Iraqi market. According to this estimate, wood sawdust concrete might be an affordable replacement for conventional concrete. In other words, it has been demonstrated that WS inclusion in concrete
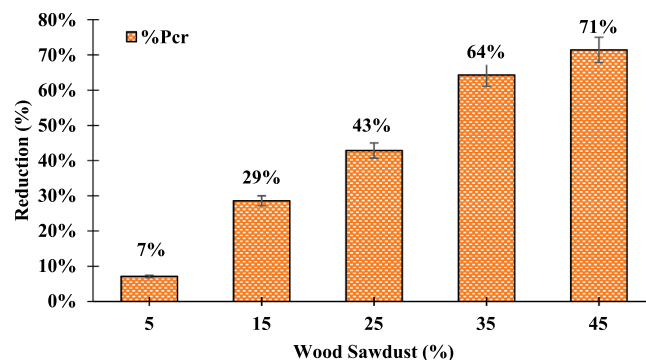


**Fig. 13.** Reduction in crack loads (%).
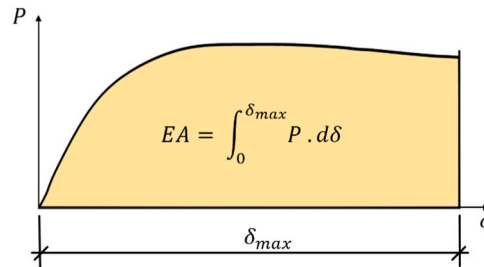
**Fig. 14.** Reduction in ultimate loads (%).



**Fig. 15.** Energy absorption calculation criterion.

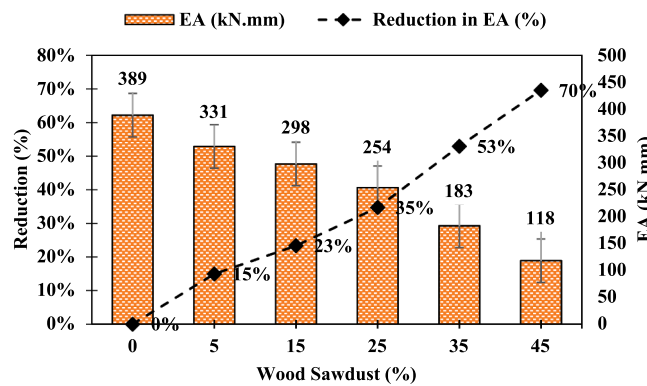$$EA = \int_0^{\delta_{max}} P \cdot d\delta$$



**Fig. 16.** Reduction in the dissipated energy with increasing the percentages of WS.

**Table 8**
Cost analysis and economy factor (cost index).

| WS (%) | FA (kg/m$^3$) | Cost (USD) | CA (kg/m$^3$) | Cost (USD) | Cement (kg/m$^3$) | Cost (USD) | Total cost (USD/m$^3$) | $f'c$ (MPa) | Economy factor ($fc'$/cost) (Strength/cost) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 890 | 7.81 | 1082 | 4.86 | 385 | 28.21 | 40.88 | 32.47 | 0.79 |
| 5 | 846 | 7.42 | 1082 | 4.86 | 385 | 28.21 | 40.49 | 30.11 | 0.74 |
| 15 | 757 | 6.64 | 1082 | 4.86 | 385 | 28.21 | 39.71 | 28.62 | 0.72 |
| 25 | 668 | 5.86 | 1082 | 4.86 | 385 | 28.21 | 38.92 | 25.86 | 0.66 |
| 35 | 579 | 5.08 | 1082 | 4.86 | 385 | 28.21 | 38.14 | 24.06 | 0.63 |
| 45 | 490 | 4.30 | 1082 | 4.86 | 385 | 28.21 | 37.36 | 22.85 | 0.61 |

is cost-effective. Fig. 17 also depicts the impact of substituting sawdust for FA on the produced concrete's aggregate cost estimate. Additionally, money was saved by using sawdust at a high rate (45 %) in place of FA.

Furthermore, measurable durability indicators must be used to encourage the creation and use of minimal environmental impact building materials. It is stated that the combustion of 1 kg of wood generates between 1.65 and 1.80 kg of $CO_2$, depending on the type used. Over the past 250 years, greenhouse gas emissions, particularly $CO_2$ emissions, have increased substantially due to energy
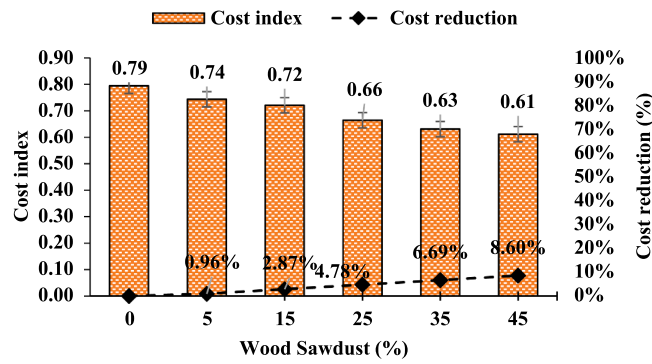
**Fig. 17.** Cost analysis.

production. The amount of $CO_2$ in the atmosphere has increased from 270 to 370 (ppm) Giga-tons. [38,39]. Concerning the sawdust concrete design, the GWP (global warming potential [kg of carbon dioxide – equiv/m$^3$]) is reduced throughout the escalating of wood waste ratio [33]. Using WS in lightweight or normal concrete construction instead of burning it will reduce $CO_2$ emission to the atmospheric layers. It was documented that the preparation of cement, coarse aggregate, fine aggregate, and water results in producing 1000 kg $CO_2$ equiv/ton, 45.9 kg $CO_2$ equiv/ton, 13.90 kg $CO_2$ equiv/ton, and 0.42 kg $CO_2$ equiv/ton (or 0.34 kg $CO_2$ equiv/ litre) respectively [40]. The amount of $CO_2$ emission for the concrete mixture material in this study follows this criterion, as shown in Eq. (3), where $Q_i$ is the total emission of $CO_2$. The results in Fig. 18 show the impact of using various ratios of wood sawdust on the $CO_2$ emission per unit concrete batch mixture used in this study.

$$CO_2 \quad production = \sum_{i=1}^{n} Q_i \times CO_{2-equiv.} \tag{3}$$

## 4. Conclusion

Experimental and environmental investigations on the impacts of wood sawdust on the performance of reinforced concrete beams have gained significant attention in recent years. Wood sawdust, a byproduct of timber processing, presents both challenges and opportunities in the field of construction materials. This research aims to explore the effects of incorporating wood sawdust as a partial replacement for fine aggregates in reinforced concrete beams. The use of wood sawdust in concrete offers potential advantages such as reducing the environmental impact associated with the disposal of sawdust waste, as well as potentially enhancing the mechanical properties of the concrete. Thus, it can be expected that this research will fill in the information gap about how sawdust affects the characteristics of concrete and, in the end, assist manufacturers in expanding the use of sawdust concrete as an insulating material for commercial usage. Therefore, this study aimed to explore the structural performance, energy absorption, crack configurations, failure modes, and cost and environmental impacts of concrete beams with different WS contents under structural load. Six reinforced concrete beams with varying ratios of wood sawdust (5 %, 15 %, 25 %, 35 %, and 45 %) in place of fine aggregates were built to assess the strength of wood sawdust RC beams (WSCB). As a baseline, the normal beam was compared to the WSCB beams. Based on the study's findings, the following conclusions are offered:

- The fresh properties were affected due to adding the wood sawdust percentages. The workability (slump reading) of the sawdust concrete decreased by (7−47) % when escalated the percentage of WS was (5−45) %. Also, the density was reduced (5−41) % by increasing the WS ratios (5−45) %.
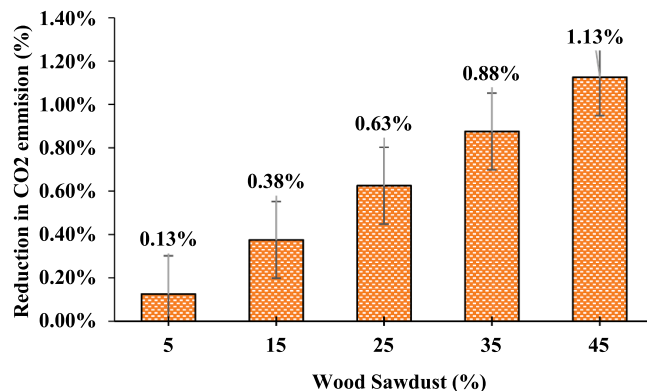


**Fig. 18.** Reduction in $CO_2$ emission due to existence of WS.

- Despite the maximum decrease in compressive strength from 33.82 *MPa* to 22.1 *MPa*, this reduction (30 %) is still within the limits of standard lightweight to moderate concrete strength.
- Ultimate and crack loads were reduced by 71 % and 51 %, respectively, for the maximum addition of 45 % wood sawdust.
- Regarding load-deflection responding, the wood saw-reinforced concrete beams displayed approximately the same shear behaviors comparable to those of the control beam.
- For WSCB beams, significant cracks were seen through the shear span region for WSCB-45 beam that applied WS at a rate of 45 %.
- Approximately six beams have the same conventional failure mode of shear due to the critical diagonal cracks, concrete fiber crushing underneath the load points, and the connection failure of the tension reinforcement close to the beam supports.
- During the monotonic loading, the dissipated energy from the control RC beam is higher than sawdust concrete beams.
- Despite the disadvantages of the attendance of WS, including decreasing the compressive strength, the wood sawdust is still one of the significant materials that strengthen the economic factor and reduce the $CO_2$ emission and cost.
- By minimizing the use of conventional resources, proper use of WS in construction materials would significantly safeguard the ecosystem and lower the emission of $CO_2$.
- Further future research is required to investigate more knowledge to be used when dealing with structural safety assessment throughout the utilization of wood sawdust in construction.

## CRediT authorship contribution statement

**Ali A. Abdulhameed:** Conceptualization, Methodology / Study design, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Mahir M. Haso:** Conceptualization, Methodology / Study design, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Amjad Ali K. Sharb:** Conceptualization, Methodology / Study design, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Ammar N. Hanoon:** Conceptualization, Methodology / Study design, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Mugahed Amran:** Methodology / Study design, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing, Visualization, Funding acquisition. **Hassan M. Magbool:** Methodology / Study design, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing, Visualization. **Yaser Gamil:** Methodology / Study design, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing, Visualization , Funding acquisition.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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## References

[1] M.Z. Jumaat, U. Johnson Alengaram, H. Mahmud, Shear strength of oil palm shell foamed concrete beams, Mater. Des. 30 (6) (2009) 2227–2236, https://doi.org/10.1016/j.matdes.2008.09.024.

[2] H.M. Mahmod, A.F.N. Aznieta, S.J. Gatea, Evaluation of rubberized fibre mortar exposed to elevated temperature using destructive and non-destructive testing, KSCE J. Civ. Eng. 21 (4) (2017) 1347–1358, https://doi.org/10.1007/s12205-016-0721-0.

[3] K. Gunasekaran Kumar, P, Lightweight concrete using coconut shells as aggregate. in: Proceedings of the ICACC-2008 International conference on Advances in Concrete and Construction, Hyderabad, India. 2008.

[4] M.M. Hason, M.H. Mussa, A.M. Abdulhadi, Flexural ductility performance of hybrid-recycled aggregate reinforced concrete T-beam, Mater. Today Proc. (2021), https://doi.org/10.1016/j.matpr.2020.11.747.

[5] A.A.K. Sharba, A.A.G. Abu Altemen, M.M. Hason, Shear behaviour of exploiting recycled brick waste and steel slag as an alternative aggregate for concrete production, Mater. Today Proc. 42 (2021) 2621–2628, https://doi.org/10.1016/j.matpr.2020.12.591.

[6] A.A. Abdulhameed, A.N. Hanoon, H.A. Abdulhameed, Q.S. Banyhussan, A.S. Mansi, Push-out test of steel–concrete–steel composite sections with various core materials: behavioural study, Arch. Civ. Mech. Eng. 21 (1) (2021) 17, https://doi.org/10.1007/s43452-021-00173-y.

[7] A.N. Hanoon, A. Abdulhameed, M.M. Kharnoob, H.A. Abdulhameed, Push-out test of steel-concrete-steel composite section for pre-installation and post-installation techniques of shear connectors, Key Eng. Mater. 862 (2020) 12–16, https://doi.org/10.4028/www.scientific.net/KEM.862.12.

[8] A.A. Abdulhameed, A.H. Al-Zuhairi, S.R. Al Zaidee, A.N. Hanoon, A.W. Al Zand, M.M. Hason, H.A. Abdulhameed, The behaviour of hybrid fiber-reinforced concrete elements: a new stress-strain model using an evolutionary approach, Appl. Sci. 12 (4) (2022), https://doi.org/10.3390/app12042245.

[9] Z.M. Mohammed, A.A. Abdulhameed, H.K. Kazim, Effect of alkali - activated natural pozzolan on mechanical properties of geopolymer concrete, Civ. Environ. Eng. 18 (1) (2022) 312–320, https://doi.org/10.2478/cee-2022-0029.

[10] K. Gunasekaran, R. Annadurai, P.S. Kumar, Long term study on compressive and bond strength of coconut shell aggregate concrete, Constr. Build. Mater. 28 (1) (2012) 208–215, https://doi.org/10.1016/j.conbuildmat.2011.08.072.

[11] S. Assiamah, S. Agyeman, K. Adinkrah-Appiah, H. Danso, Utilization of sawdust ash as cement replacement for landcrete interlocking blocks production and mortarless construction, Case Stud. Constr. Mater. 16 (2022), e00945, https://doi.org/10.1016/j.cscm.2022.e00945.

[12] S.A. Salih, A.M. Kzar, Studying the utility of using reed and sawdust as waste materials to produce cementitious building units, J. Eng. 21 (10) (2015) 36–54.

[13] P. Shafigh, M.Z. Jumaat, H.B. Mahmud, U.J. Alengaram, A new method of producing high strength oil palm shell lightweight concrete, Mater. Des. 32 (10) (2011) 4839–4843, https://doi.org/10.1016/j.matdes.2011.06.015.

[14] J. Ahmad, R. Martínez-García, J. de-Prado-Gil, A.A. Pasha, K. Irshad, M. Bourchak, Mechanical performance of sustainable high strength ductile fiber reinforced concrete (HSDFRC) with wooden ash, Sci. Rep. 12 (1) (2022) 4306, https://doi.org/10.1038/s41598-022-08134-y.

[15] U.S.E.P. Agency. Facts and figures about materials, waste and recycling. Facts and Figures 2022.

[16] R. Siddique, M. Singh, S. Mehta, R. Belarbi, Utilization of treated saw dust in concrete as partial replacement of natural sand, J. Clean. Prod. 261 (2020), 121226, https://doi.org/10.1016/j.jclepro.2020.121226.

[17] W.A. Butt, K. Gupta, J.N. Jha, Strength behaviour of clayey soil stabilized with saw dust ash, Int. J. Geo-Eng. 7 (1) (2016) 18, https://doi.org/10.1186/s40703-016-0032-9.

[18] G. Charis, G. Danha, E. Muzenda, A review of timber waste utilization: challenges and opportunities in Zimbabwe, Procedia Manuf. 35 (2019) 419–429, https://doi.org/10.1016/j.promfg.2019.07.005.

[19] F.F. Udoeyo, P.U. Dashibil, Sawdust ash as concrete material, J. Mater. Civ. Eng. 14 (2) (2002) 173–176, https://doi.org/10.1061/(ASCE)0899-1561(2002)14:2 (173).

[20] R. Siddique, M. Singh, A.K. Singhal, Use of unprocessed wood ash as partial replacement of sand in concrete, Acids Mater. J. 116 (6) (2019) 77–86.

[21] Y. Cheng, W. You, C. Zhang, H. Li, J. Hu, The implementation of waste sawdust in concrete, Engineering 5 (12) (2013) 943, https://doi.org/10.4236/eng.2013.512115.

[22] O.J. Oyedepo, S.D. Oluwajana, S.P. Akande, Investigation of properties of concrete using sawdust as partial replacement for sand, Civ. Environ. Res. 6 (2) (2014) 35–42.

[23] D.Y. Osei Jackson, E.N. Compressive, strength of concrete using sawdust as aggregate, Int. J. Sci. Eng. Res. 7 (4) (2016) 1349–1353.

[24] W. Ahmed, R.A. Khushnood, S.A. Memon, S. Ahmad, W.L. Baloch, M. Usman, Effective use of sawdust for the production of eco-friendly and thermal-energy efficient normal weight and lightweight concretes with tailored fracture properties, J. Clean. Prod. 184 (2018) 1016–1027, https://doi.org/10.1016/j.jclepro.2018.03.009.

[25] M. Bederina, L. Marmoret, K. Mezreb, M.M. Khenfer, A. Bali, M. Quéneudec, Effect of the addition of wood shavings on thermal conductivity of sand concretes: experimental study and modelling, Constr. Build. Mater. 21 (3) (2007) 662–668, https://doi.org/10.1016/j.conbuildmat.2005.12.008.

[26] M. Mageswari Vidivelli, B, the Use of Sawdust Ash as Fine Aggregate Replacement in Concrete. 2009.

[27] A. Uchechukwu Elinwa, Effect of addition of sawdust ash to clay bricks, Civ. Eng. Environ. Syst. 23 (4) (2006) 263–270, https://doi.org/10.1080/10286600600763149.

[28] R.S. Ravindrarajah, C. Carroll, N. Appleyard, Development of sawdust concrete for block making. Centre for Infrastructure, Res., Univ. Technol., Syd., Aust. 23 (2001).

[29] F. Batool, K. Islam, C. Cakiroglu, A. Shahriar, Effectiveness of wood waste sawdust to produce medium- to low-strength concrete materials, J. Build. Eng. 44 (2021), 103237, https://doi.org/10.1016/j.jobe.2021.103237.

[30] B. Ramme, ACI 229R-99 controlled low-strength materials, Am. Concr. Inst. 99 (2005) 1–15.

[31] ACI-211.1, Standard practice for selecting proportions for normal, heavyweight, and mass concrete. in: ACI Manual of Concrete Practice, Part 1, American Concrete Institute, Detroit, Mich, 1991.

[32] H. Alabduljabbar, G.F. Huseien, A.R. Sam, R. Alyouef, H.A. Algaifi, A. Alaskar, Engineering properties of waste sawdust-based lightweight alkali-activated concrete: experimental assessment and numerical prediction, Materials 13 (23) (2020), https://doi.org/10.3390/ma13235490.

[33] T. Alexandru, B. Marinela, D. Laura, B. Irina, Mechanical and environmental performances of concrete using recycled materials, Procedia Manuf. 32 (2019) 253–258, https://doi.org/10.1016/j.promfg.2019.02.211.

[34] Sa. Odaa Hason, M.M. Sharba, A.A.K, Self-compacting concrete beams reinforced with steel fiber under flexural loads: a ductility index evaluation, Mater. Today Proc. (2021), https://doi.org/10.1016/j.matpr.2020.12.313.

[35] M.M. Hason, A.N. Hanoon, A.W. Al Zand, Abdulhameed, A.A. Al-Sulttani, A.O, Torsional strengthening of reinforced concrete beams with externally-bonded fibre reinforced polymer: an energy absorption evaluation, Civ. Eng. J. 6 (2020) 69–85, https://doi.org/10.28991/cej-2020-SP(EMCE)-07.

[36] A.A.K. Sharba, M.M. Hason, A.N. Hanoon, D.N. Qader, M. Amran, A.A. Abdulhameed, A.W. Al Zand, Push-out test of waste sawdust-based steel-concrete – steel composite sections: experimental and environmental study, Case Stud. Constr. Mater. 17 (2022), e01570, https://doi.org/10.1016/j.cscm.2022.e01570.

[37] M.M. Hason, A.N. Hanoon, S.J. Saleem, F. Hejazi, A.W. Al Zand, Characteristics of experimental ductility energy index of hybrid-CFRP reinforced concrete deep beams, SN Appl. Sci. 3 (2) (2021) 200, https://doi.org/10.1007/s42452-021-04202-6.

[38] M.M. Hason, A.O. Al-Sulttani, I.S. Abbood, A.N. Hanoon, Emissions investigating of carbon dioxide generated by the iraqi cement industry, IOP Conf. Ser Mater. Sci. Eng. 928 (2020), 022041, https://doi.org/10.1088/1757-899x/928/2/022041.

[39] B.L. Gadiga, K.F. Jigumtu, H. Tammi, Domestic energy utilization and potentials of alternative sources of energy in mubi metropolis, Geosfera Indones. 3 (2) (2018) 90–102.

[40] H. Ghayeb, H.A. Razak, N. Sulong, A. Hanoon, F. Abutaha, H. Ibrahim, M. Gordan, M. Alnahhal, Predicting the mechanical properties of concrete using intelligent techniques to reduce $CO_2$ emissions, Mater. De. Constr. 69 (334) (2019), e190, https://doi.org/10.3989/mc.2019.07018.