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An Up-to-Date Review of Sawdust Usage in Construction Materials

Nadia Ghadhanfer Hikmet

Department of Materials, College of Engineering, Mustansiriyah University, Baghdad, Iraq

ABSTRACT

Carbon emissions and expensive raw building materials with a high risk of being scarce in the future would expose both the global nature and sustainability of construction to danger. In response, many countries are drawing modern strategies for a greener environment by adopting recycled and eco-friendly materials in construction including waste, used wood or sawdust wastes. The present article brings the most distinctive studies and promising methods related to sawdust presence in concrete and bricks. Both physical and mechanical properties were covered. Sawdust waste was successfully found to partially replace cementitious materials or natural aggregates without adverse deterioration. Most studies suggest a 5 to 20% volume or weight content to be the optimum and safe sawdust replacement level. However, maintaining desirable strength with a high sawdust content (≥20%) requires extra treatment to the sawdust including but not limited to boiling, washing, adding sodium silicate, and curing with sodium sulphate bath. Aside from that, adding sawdust was profoundly effective at reducing density, and improving thermal and sound insulation in buildings. The findings herein promote the utilization of sawdust in structural elements such as interior and exterior walls, ceilings, partition blocks, and non-load-bearing panels. This scope offers an opportunity to create a greener environment, affordable construction, and proficient investment in natural resources.

Keywords: Sawdust, Recycled material, Lightweight concrete, Thermal conductivity, Sound insulation.

1. INTRODUCTION

Recent years have witnessed a rapid escalation of sustainable and eco-friendly materials in construction. The main reasons for this shift are to mitigate the carbon emissions to the environment and reduce the exhaustive consumption of the earth's raw materials **(Majeed, 2011; Gan et al., 2019; Lim et al., 2019)**. Such a process includes replacing the main substances with recycled or alternative abundant raw materials while maintaining the same

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*Corresponding author

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desirable performance as possible. Traditional concrete production, for instance, is considered by far one of the heaviest resource extractions of raw materials mounting at as the second largest consumed material after water with three tons per capita each year **(Gagg, 2014)**. Thus, numerous works have been committed to control such consumption by introducing alternative substances into the concrete mixtures or cement mortars including sawdust, fly ash, clay, natural pumice, fibers, glass, recycled aggregates, etc. **(Batayneh et al., 2007; Abdul-Wahab et al., 2021; Abbas and Abbas, 2023)**.

Sawdust is a byproduct waste resulting from woodworking such as sawing, drilling, cutting or sanding the wood by various tools. Depending on woodworking techniques, sawdust can be released in various forms and sizes as shown in **Fig. 1** like fibers, chips, powder or even coarser chunks **(Ogundipe and Jimoh, 2009)**. Sawdust can be derived from many natural wood resources, for instance, cottonwood, birch, oak or maple offers fine particle sizes of sawdust, while cedar and Norway pine seem to make coarser particles. The former tree source is said to produce sawdust concrete with satisfying properties **(Appiah, 2010)**. Cellulose (45-50%), lignin (23-30%), hemicelluloses (20-30%), and extraneous materials (e.g. acids, soluble sugar, oil, waxes, resins, etc.) are the main elements of sawdust **(Mallakpour et al., 2021)**. Sawdust mainly contains silicon, aluminum, calcium, and ferric oxides with more than 70% of its composition **(Raheem et al., 2017)**. Chemically, sawdust largely constitutes carbon and oxygen with 60.8% and 33.8%, respectively, besides minor presence of hydrogen (5%) and nitrogen (1%) **(Chemani and Chemani, 2012; Tulashie et al., 2023)**. In the United States alone, statistics show about 64 million tons of wood waste are generated per year, in 40% of that waste is positioned in landfills without re-use **(Sharba et al., 2022)**. As a result, open dumping or burning sawdust in the USA to produce energy are the most practical approaches to dispose of sawdust. doing so would cause harsh damage to both human health and the environment by increasing CO_2 emissions and respiratory complications **(Deac et al., 2016)**. Other life-threating side effects related to the untreated sawdust might be blocking the streamlets and potential wildfire **(Fregoso-Madueño et al., 2017; Zepeda-Cepeda et al., 2021)**. Therefore, an efficient recycling solution is necessary to minimize the adverse effects of waste sawdust **(Turgut, 2007)**.

Figure 1. Sawdust wastes with different particle sizes (a) fine (b) coarse

One of the successful approaches to reuse waste sawdust is introducing it to construction materials. Although the reuse is seen in different ways, sawdust applications are limited to certain cases such as insulation, acoustic panels, decorative parts, particleboard, partition walls and ceiling boards **(Ahmad et al., 2021)**. In other words, sawdust is typically utilized where structural elements are not subjected to heavy loads. Sawdust studies have drawn considerable attention in the last fifty years **(Olaiya et al., 2023)**. Research was focused on the inclusion of sawdust in different types of concrete and mortars as full or partial replacement to cementitious composition or natural aggregates with various mix ratios. Such interesting material triggers to consolidate a comprehensive overview to provide pivotal knowledge within this research field.

The current work seeks to cover the most valuable methodologies and findings associated with sawdust. The outcomes are expected to unveil new hypothesis to study or areas that require further examination. Thus, the paper is sectioned to report on the physical properties of sawdust, and the use of sawdust in different types of concrete and construction materials.

2. PHYSICAL PROPERTIES OF SAWDUST

2.1. Density

Depending on wood species, woodworking techniques, and the presence of additives, the density of sawdust varies distinctively. Such physical factors not only affect storage, transportation processes, or combustion efficiency but also the capability of absorption, sound proofing, and indoor and outdoor thermal insulation (i.e., thermal conductivity) **(Bwayo and Obwoya, 2014)**. According to 16 wood species examined by **(Rizki et al., 2010)**, the particle density of sawdust is estimated between 80 to 350 kg/m^3. The authors concluded that wood density make a positive correlation with the particle density of sawdust. Also, the high particle density tended to offer the lowest porosity and highest water retention. **(Xing et al., 2015)** stated that the dried density of poplar sawdust is estimated to be 178 kg/m^3. As a part of a fuel quality study, four different Oak species from northeastern Mexico was analyzed by **(Núñez-Retana et al., 2019)**. The research indicated that the barked sawdust density is generally limited between 200-260 kg/m^3, while debarked sawdust for the same species presented relatively less values.

The light density of sawdust offers remarkable weight reduction when it is encountered in concrete or cement mortar mixes. It is generally estimated that sawdust concrete weighs 30-40% less than traditional normal concrete weigh **(Ansari et al., 2000; Awal et al., 2016)**. However, the amount of reduction is highly fluctuated due to many parameters such as wood type, pre-treatment of sawdust and sawdust replacement percentage. A comparative study accomplished by **(Aigbomian and Fan, 2013)** revealed that solid blocks made with softwood sawdust (i.e., pine and cedar) had 18% less density than their counterparts made with hardwood sawdust (i.e., beech and oak).

Replacing sand with different percentages of sawdust was proven to cause weight decline in mixed samples. **(Adebakin et al., 2012)** examined the physical properties of sandcrete blocks casted with different partial replacement of sawdust to sand. At the age of 28 days, the study presented a 10% reduction of blocks weights with 10% sawdust replacement. Similar amount of weight reduction was observed by **(Ganiron, 2014)** when sand was fully replaced by sawdust in cement-sawdust-gravel mixtures. An experiment conducted by **(Awal et al., 2016)** involving testing sawdust concrete with cement-sawdust mix ratios of 1:1, 1:2, and 1:3. The authors observed a steady density reduction as the proportion of sawdust increased. The corresponding decrease was about 27% from the mix ratio of (1:1) to (1:3). Conclusively, sawdust concrete is an advantageous construction material serving lightweight structures and economical cost besides ease of transporting when sawdust concrete is made as pre-cast elements.

2.2. Water Absorption

Owing to its nature, sawdust waste is undoubtedly susceptible to water absorption and has a remarkable ability to soak up and retain water **(Ahmed et al., 2018)**. The amount of water absorption or saturation limit differs depending upon particle size, type, pre-treatment use, initial dryness of the wood, and most importantly proportional use in the mix design. Therefore, sawdust may absorb water between 200-300% of its dry weight when fully saturated. Nevertheless, this challenging part makes sawdust unpopular among marine applications and high humid environments **(Udokpoh and Nnaji, 2023)**. With inconsiderate utilization and constant water contact, sawdust in concrete gradually degrades, leading structures to be vulnerable to rot and less durable **(Zou et al., 2020)**. Excessive water content in sawdust forms voids and weak bonds between sawdust particles and cement paste. As a result, the mechanical properties of concrete (e.g. compressive, tensile, elasticity, and rupture strength) would experience degradation. Other adverse effects on the physical properties of concrete caused by high water absorption might include dimensional mass changes (e.g. swelling), unfavorable outcomes in workability and high susceptibility to shrinkage and freeze-thaw cycles **(Nanayakkara and Xia, 2019)**. Hence, sawdust should be treated with extra care in mix design to avoid a possibility of high-water absorption, otherwise, it is not advisable to implement sawdust where structures are continuously exposed to water or moisture.

Despite the maximum allowable limit for water absorption varying amongst construction materials, **(Cheah and Ramli, 2011)** argue that the satisfying value of water absorption in most construction materials should not exceed 10%. Various research examined the water absorption of different construction materials incorporating sawdust waste. **(Elinwa and Ejeh, 2004)** tested water absorption of five mortar cubes of 50 mm dimension with ultra-fine sawdust as 15% replacement to cement. The findings indicated that the average water absorption was (0.8%), compared to the control samples (without sawdust) with (1.29%). The authors attributed this better performance to the formation of a denser microstructure caused by ultra-fine sawdust filling the voids in cement. The water absorption of masonry bricks with sawdust wastes was tested by **(Turgut and Algin, 2007)**. The study revealed that bricks with 30% sawdust waste content experienced a 50% increase of water absorption capacity compared to the control mix without sawdust. Yet, water absorption lied within the acceptable limits compared to the lightweight produced materials such as autoclaved aerated concrete where water absorption capacity captures 60% of unit mass. In relation to this, **(Raheem and Sulaiman, 2013)** found that the water absorption among sandcrete block samples increased from 9.99% with no sawdust content to 19.5% with 25% sawdust replacement to cement. The authors observed that only 5% sawdust content ended with 11.54% water absorption, resting below the 12% maximum limit requirement provided by **(BS 5628- 1, 2005)**. **(Ahmed et al., 2018)** supposed that the existence of high initial free water content is also a reason besides the porous nature behind the high ability of water absorption by sawdust. The authors noticed that increasing sawdust content in cement-based formulations from 5% to 15% led the water absorption in normal-weight concrete to increase from 1.42 to 3.62%, while lightweight concrete exhibited a 3.21% increase in water absorption when sand was replaced by 10 % of sawdust. In conclusion, sawdust wastes require carefulness in use in building materials, and 5-15% is deemed to be the optimum sawdust content in mix design to achieve acceptable outcomes.

2.3. Acoustical Insulation

Porous materials like sawdust contains tiny particles with irregular shapes. This composition creates air pockets to trap and dissipate sound waves as they transmit through sawdust structures **(Setunge and Gamage, 2016; Boubel et al., 2021)**. Sawdust has also the ability to absorb and dampen sound's intensity when densely packed into composite materials like cladding boards. These materials employ frictional forces within their fibrous structure to convert the acoustic energy into heat energy **(Asdrubali et al., 2017)**.

Incorporating wood or its substance like sawdust in building materials has been proven to be a substantial means to absorb sound vibrations and lessen noise impact. **(Chung et al., 2010)** found that featuring sand-sawdust mixture layer outperformed rubber ceiling batten clips and glass fiber wool as an isolating-damping composition against a wide range frequency. **(Chung et al., 2010)** suggested that such composite structure if included in lightweight timber based floor/ceiling system (LTFSs) is likely to be more effective than normal concrete slab systems in sound insulation. Supported by mathematical and experimental measurements, **(Chung et al., 2014)** observed that a mixture having a sand-sawdust layer was effective at damping the sound vibration frequency ranged between 10 and 200 Hz. **(Kang et al., 2012)** addressed rice hull-sawdust composite boards in interior wall applications, and light ceilings as an alternative material to the commercial boards for sound absorption. The proposed boards were compared with commercial gypsum boards and fiberboards. The study showed that the corresponding sound absorption coefficients of the composite boards were 0.20 at 500 Hz, 0.40 at 1000 Hz, and 0.40-0.55 above 1000 Hz. A favorable performance in sound absorbing was aligned with the 400 Kg/m^3 density composite boards for being two times better than gypsum boards at a frequency of 1000 Hz. Moreover, the composite boards presented larger sound absorption coefficients than the commercial gypsum boards with a range of frequency of 500-4000 Hz.

(Tiuc et al., 2014) tested and compared the sound absorption characteristics of two waste materials including recycled rubber granules and sawdust. Both materials came with 15 mm thickness and were exposed to a sound frequency range of 100-3150 Hz. The experiment indicated that both materials performed in a similar manner at sound absorption when the frequency range was 100-1600 Hz. Sawdust and recycled rubber granules granted sound absorption coefficients of 0.80 and 0.88, respectively. Yet, the rubber material behaved more effectively at sound frequency of 3150 Hz, with sound absorption coefficient of 0.58, compared to 0.38 associated with sawdust material.

(Tiuc et al., 2019) evaluated the acoustic performance of 100% flexible polyurethane foam product (100-FPF) and compared it against 50% for sawdust and 50% flexible polyurethane foam product (50-FPF). The test was carried out with a sound frequency range from 100 to 1700 Hz. The utmost sound absorption coefficient of (100-FPF) product was reported at 0.89 for a frequency of 1700 Hz. The acoustic performance of (50-FPF) product was seen effective between 100-700 Hz, whilst the (100-FPF) product was observed to be more effective for the same frequency level with a sound absorption coefficient of 0.86. On whole, introducing sawdust into different techniques of soundproofing materials provides superior curb against sound wave transmission, reflecting positively on lifestyle comfort and limiting the acoustic pollution within construction zones.

2.4. Thermal Conductivity

A thermal insulator material is normally classified when the thermal conductivity index is less than 0.07 W/mK **(Asdrubali et al., 2015)**. Wood or its byproduct including sawdust is well-known for its capability of hindering the heat transfer owing to its composition, making it an attractive element for heat insulation and low thermal conductivity. **(Bwayo and Obwoya, 2014)** assumed that the key success of low thermal conductivity of sawdust lies in creating a high porous median in the specimens and thus reducing the mean free path of heat flow. Previous studies highlighted the significance of sawdust addition in modifying the thermal conductivity of lightweight clay and concrete products. Such studies showed the ability of sawdust to limit the thermal conductivity up to 50% among clay lightweight bricks and cementitious building units (**Nyers et al., 2015; Salih and Kzar, 2015; Martínez-Molina et al., 2016)**.

An experimental study accomplished by **(Folaranmi, 2009)** to examine the thermal conductivity of clay with sawdust as an additive by (0, 1, 5, 10, 20, 30%) of amount volume. It was interesting to observe that the thermal conductivity of clay declined from 0.25 W/mK to 0.06 W/mK as 30% of sawdust was added to the clay mix. **(Cultrone et al., 2020)** argued that the addition of sawdust to solid bricks had created a new porous median by which 60% of porosity was reached with 10% in weight of sawdust addition. In response, the thermal insulation of bricks at fire temperatures (800, 950, and 1100 ^{o}C) was enhanced. Another study accounted for the thermal conductivity of earthen clay-based bricks was demonstrated by **(Charai et al., 2020)**. It was concluded that the thermal conductivity of bricks was reduced by 30% as 10% sawdust was added to the composites. The study also showed that clay-sawdust composites provided 21% and 5.3% reduction to the energy consumption of conventional and traditional residential buildings, respectively. The positive influence of sawdust was also in agreement with a study accomplished by **(Phonphuak et al., 2020)**, whereas the thermal conductivity of porous fired clay bricks dropped by almost 50% (i.e., from 0.47 to 0.22 W/mK) when 10% by weight of mix was incorporated by sawdust.

Over the years, researchers have made considerable tests to improve the thermal conductivity of cement-based materials. It is reported that the thermal conductivity of normal strength concrete (i.e., conventional concrete) with a density range between 2100-2400 Kg/m^3 is set between 1.40-1.75 W/mK **(Asadi et al., 2018)**, but it could also reach 2.47 W/mK **(Sales et al., 2010)**. It is apparent that thermal conductivity is profoundly affected by mix design and the existence of sawdust as a replacement to fine or coarse aggregates. **(Ogundipe and Jimoh, 2009)** examined various concrete mixes of cement, sand, and sawdust as (1:1.5:3, 1:2:4, 1:3:6, and 1:4:8). Test results showed that the mean thermal conductivity of all mixes at the age of 28 days was 0.218 W/mK with a standard deviation of 0.021. Another comparison study conducted by **(Sales et al., 2010)** involved full replacement of coarse aggregate by a composite of sawdust and sludge. The mass ratio of the concrete with the composite was (1:2.5:0.67:0.6) of cement, sand, composite, and water, respectively. The findings presented the ability of the composite to reduce thermal conductivity by 23%. The advantage of sawdust utilization to control the heat transfer and satisfactorily minimize thermal conductivity was further confirmed by several other studies **(Cheng et al., 2013; Hu, 2014; Memon et al., 2017; Abdul Ameer, 2018; Zou et al., 2020)**.

3. SAWDUST IN CONSTRUCTION APPLICATIONS

3.1. Sawdust in Masonry Wall System

The rapid growth of metropolitan areas worldwide puts the construction materials on high demand and extensive use. This makes the cost of building is unlikely affordable in most circumstances. Not to mention that the idea of conventional bricks or concrete to be under shortening supply in the future is becoming a true concern. Therefore, introducing waste raw materials like sawdust into construction is thought to be a feasible and alternative solution to achieve low cost and sustainability **(Ahmad et al., 2021)**. Sandcrete blocks or concrete bricks comprise of cement, sand, and water, with a possible coarse aggregate addition in some limited cases **(Denis et al., 2002)**. Numerous studies were carried out to examine the influence of sawdust wastes presence on the mechanical properties of bricks.

(Turgut and Algin, 2007) investigated the mechanical properties of concrete bricks with limestone powder and sawdust wastes combination. The mix design contained (10, 20, and 30%) sawdust replacement. Test results showed that using 30% sawdust replacement resulted in 71% and 22% reduction in compressive and flexural strength, respectively. The corresponding values of such reduction were 7.2 and 3.08 MPa, respectively. Despite this drastic reduction, concrete bricks with 30% replacement level of sawdust wastes satisfied the minimum requirement of building material application in BS6073. This composition offered 65% less weight than conventional concrete bricks. In relation to this, **(Turgut, 2007)** further examined the mechanical properties of concrete bricks including different particle sizes of sawdust wastes (i.e., fine, coarse, and mixed) for the same mix design proportions. Findings revealed that coarse size of sawdust wastes was the best choice to lessen the drastic reduction in compressive and flexural strength, especially among specimens with 10-20% sawdust replacement. The study also showed that using a combination of limestone powder and sawdust wastes led to high energy absorption capacity among specimens, by which did not experience a sudden brittle fracture.

(Adebakin et al., 2012) addressed the compressive strength of sandcrete blocks with different sawdust replacement to sand. Test results recommended 10% sawdust replacement as an optimum level to be adopted, by which beyond the compressive strength would suffer from drastic decline. Similar recommendation was concluded from a study carried out by **(Raheem and Sulaiman, 2013)**, whereas 10% replacement sand with sawdust was set to be use for non-bearing walls in buildings. Compressive and flexural strengths were among parameters tested by **(Sasah and Kankam, 2017)**. A mix design ratio of cement, sand (1:3) was considered, where sand was partially replaced by sawdust with a range of 5 up to 50%. The authors suggested that sawdust content with (5-10%) replacement would be the best level to achieve adequate properties of bricks. However, such findings are most likely to be recommended on interior wall applications. Likewise, test results obtained from works done by **(Surabhi et al., 2017; Okoroafor et al., 2017)** advised the use of sawdust-sand-cement composite in light structural members where heavy loads are not subjected.

Most recent studies endeavor to obtain sufficient results from composite bricks with minimum allowable sawdust addition. **(Ghimire and Maharjan, 2019)** performed two design strengths of concrete bricks including M15 and M20 with cement, sand, coarse aggregate mix ratio of (1:2:4) and (1:1.5:3), respectively. Sand was replaced by sawdust at 10, 20, 30%. The corresponding compressive strength of control samples (without sawdust) was 14.73 and 17.5 MPa for M15 and M20 concrete bricks, respectively. Test results showed that the compressive strength of concrete bricks with 10% sawdust content was 11.23 and 13.68 MPa for M15 and M20 concrete bricks, respectively. However, further unfavorable decline in compressive strength was observed with 20% sawdust content samples. Based on an experiment conducted by **(Farazela et al., 2021)**, composite sand cement bricks were tested aligned with (1-5%) sawdust replacement to sand. The authors concluded that (1-2%) sawdust content was the optimum values to maintain the desirable compressive strength despite being associated with slightly higher water absorption. Clay-sawdust bricks under elevated temperatures ranging from 70 to 850 °C were investigated by **(Alabduljabbar et al., 2021)**. The results indicated a 22% reduction in compressive strength and 2 hours firing time decrease when 4% sawdust was added. A further 48% reduction in compressive strength and 4 hours firing time decrease was reported when 4% sawdust was added.

(Assiamah et al., 2022) attempted to introduce satisfying performance of landcrete interlocking blocks utilizing sawdust ash as cement replacement. The mix proportion of cement, laterite soil was (1:6) with 0, 10, 20, and 30% sawdust replacement to cement. At the age of 28 days, the compressive strength was found to be 6.20, 6.52, 6.32, and 5.73 MPa, respectively. The authors concluded that the use of 20% sawdust content meets the minimum limit (i.e., 2.75 MPa) provided by Ghana building code for load-bearing masonry structures. Conclusively, the addition of sawdust waste in masonry structures does not necessarily improve the mechanical properties, yet it maintains the minimum allowable performance if used with specific proportion. Moreover, sawdust waste contributes to lightweight structures, economical cost, and an eco-friendly environment.

3.2. Sawdust in Normal Strength Concrete (NSC)

Concrete still ceases to be among the most used and favored materials in buildings worldwide **(Amiri et al., 2021; Khan et al., 2022)**. However, this material holds another challenging side. For instance, cement, which is one of the main elements of concrete, generates an estimate of 1350 million tons of CO_2 each year, amounting at 7% of the global greenhouse gas emissions **(Cleetus et al., 2018)**. To mitigate such a harsh effect on the environment and conserve natural raw resources, remarkable scientific research has been made to succeed partially or fully replacing cement and natural aggregates with waste materials. Employing sawdust waste in concrete dates back to the mid of the last century. But for the purpose of simplicity, sawdust-concrete based studies in the last decades are only exemplified herein. The line of research on sawdust-concrete is divided into two main paths, one with cement replacement, and the other with aggregates replacement.

Beginning with cement replacement intention, **(Saeed, 2013)** examined the mechanical properties of concrete with cement replaced by sawdust at 5-35%. Sawdust was pretreated before use by boiling water (i.e., phase 1), and by boiling water and waterproofing material addition (i.e., phase 2). When compared with untreated sawdust samples, test results showed significant improvement in both compressive and flexural strengths with phase 1 treatment, while further improvement was seen with phase 2 treatment. **(Malik et al., 2015)** noticed 17% compressive strength enhancement of concrete with cement being 10% replaced by sawdust. The authors presumed that sawdust can be taken as a pozzolanic material due to the presence of (SiO_2 + Al_2O_3 + Fe_2O_3) with more than 70% in its chemical composition. In contrast, **(Awal et al., 2016)** observed a steady decline in compressive, tensile, and flexural strengths with the increase amount of sawdust. The work was experimentally conducted with specimens involving cement to sawdust ratios of (1:1, 1:2, and 1:3). This negative effect is expected as sawdust is porous by nature with a high ability of water absorption and being slow pozzolanic reaction material **(Yang et al., 2016)**. This observation agrees with that of **(Ikponmwosa et al., 2020)** where they classified sawdust as class C pozzolan despite such a material had 74.31% combination of (SiO_2 + Al_2O_3 + Fe_2O_3) in its chemical composition. Their study revealed a decrease in workability and mechanical properties of concrete mixtures with the use of sawdust as a partial replacement of cement up to 20%.

(Meko and Ighalo, 2021) had ordinary portland cement (OPC) replaced by a certain sawdust ash, namely "Cordia Africana". The experiment initially included a control concrete sample having a mix design ratio of cement, sand, aggregate of (1:2.35:3) with a target design concrete strength of 25 MPa. The cement was then partially replaced by sawdust at various percentages (5, 10, 15, 20%). While the initial and final setting time increased due to the addition of sawdust, both workability and compressive strength were decreased in association with 10, 15, and 20% sawdust content. Interestingly, concrete mixture with 5% sawdust content experienced a modified compressive strength in comparison to the control sample. **(Onyechere, 2022)** recommended a 10% sawdust content as a successful partial cement replacement to enhance the compressive strength. The author promoted such addition among concrete structures, but with concrete above 10% sawdust content, it is likely to be only adequate for light load bearing structures.

The other research line has addressed sawdust utilization as a partial aggregate replacement (mostly sand replacement). **(Soundhirarajan and Abirami, 2018)** attempted to acquire concrete with a design compressive strength of 20 MPa by replacing the natural sand with a combination of sawdust and robo sand. The latter material is obtained from the dust of crushing stones in quarries. Test results showed a possibility to produce M20 concrete with natural sand being 50% replaced by 10% of sawdust and 40% of robo sand. **(Oyedepo et al., 2014)** examined concrete strength with sand being replaced by sawdust as 25-100%. The concrete mix ratio of cement, sand, and coarse aggregate was (1:2:4). The findings reported a drastic decline in compressive strength as sawdust content increased. However, it was noted that using 25% sawdust content can still be possible to meet a minimum adequate performance of lightweight concrete. The mechanical properties of concrete incorporating partial sand replacement with sawdust at (5-25%) were studied by **(Sawant et al., 2018)**. The mix design ratio of (1:1.62:2.83) was prepared to produce M25 concrete. Despite a remarkable reduction in compressive, splitting, and flexural strengths was reported with sawdust content, the corresponding optimum sand replacement to achieve satisfying results was set at 5%.

(Siddique et al., 2020) found that the addition of dry sawdust as 5 and 10% sand replacement caused a substantial drop in compressive strength by 32 and 72%, respectively. Due to this, the authors proposed two unique methods to compensate such loss. One included keeping sawdust in water for 24 hours and using it in a concrete mixture as saturated surface dry sawdust with silica fume addition in some cases. The other method incorporated sodium silicate treated sawdust with high cement content in concrete mixture. For concrete with 5 and 10% water treated sawdust content, compressive strength was found to be 6.3 and 30.3% less than the control sample. As for concrete with 5 and 10% sodium silicate treated sawdust content, compressive strength was found to be 7.55 and 32.02% less than the control sample. However, adding silica fume as a substitute of cement did not make a big change in results. It was evident that pretreating sawdust helps to lessen the acuteness loss in concrete strength and keeps the concrete applicable in construction.

The post-treatment approach for concrete-sawdust mixture was also addressed by **(Batool et al., 2021)**. That included immersing samples in a sodium sulphate bath for 28 days and comparing the results with that of untreated concrete-sawdust samples. Once again, it was apparent that the sulphate exposure enabled the concrete to gain higher compressive strength. While the increase among the control sample (0% sawdust content) was reported at 6.2%, the enhancement among concrete mixtures with 10-60% sawdust content was recorded at 3.6, 5.2, 23.8, 28.7, 32.6, and 16.8%, respectively. The authors attributed such improvement to the formation of crystalline hydrated products which filled the cracks and openings during the curing stage. **(Dias et al., 2022)** conducted an experiment to assess the mechanical properties of concrete incorporating wood chips and sawdust. With the intention to replace aggregates, various contents of wood chips, sawdust, or combined were used (5-25%). The outcomes showed that concrete mixtures with a combination of wood chips and sawdust experienced the most adverse mechanical performance (i.e., compressive and flexural strengths), while utilizing sawdust only was proved to have lesser effect. However, all concrete mixtures met the design compressive strength above 30 MPa irrespective the compositions. **Table 1** summarizes the work and findings of the studies that were mentioned above in this section. There is insufficient data available on splitting, and flexural strength. It is, thereby, essential to examine such aspects with the presence of sawdust. On whole, concrete having sawdust content are proved to be applicable in structural and non-structural areas if carefully treated before or after use in concrete mixture. The inclusion of sawdust helps reduce the overall weight of structures, cost, and greenhouse gas emissions.

3.3. Sawdust in Lightweight Concrete (LWC)

Lightweight concrete is manufactured by various lightweight aggregates, such as expanded clay, shale, fly ash, furnace slag, pumice, tuff, etc. **(Thienel et al., 2020; Abbas, 2022)**. Those materials are mixed with cement, water, and other additive materials (if necessary) to provide specific concrete with oven-dry density ranges from 800-2000 kg/m^3. Structural lightweight concrete with an adequate mix design can be used in roofs, panels, and pre-cast systems, resulting in reduced dead load on foundations **(Lotfy et al., 2016)**. It can also be used as interior and external walls due to its sufficient thermal insulation and fire resistance **(Fares et al., 2015)**.

Sawdust waste is a high potential material to be considered in lightweight concrete due to its low-density nature and effective thermal insulation. **(Sojobi, 2016)** tested the bulk density and compressive strength of lightweight concrete paving units with sand being partially replaced by sawdust. With a mix design ratio of (1:2:4) and 28 curing days, the recorded compressive strength decline was 47.3, 61.8, and 73.6%, and the mean bulk density dropped at 7.16, 17.48, and 24.01% at 5, 10, and 15% sawdust replacement. Nonetheless, sawdust with 5-10% replacement level met the minimum compressive strength requirement of 3.45 MPa for low bearing load applications like pedestrian sidewalks, building premises, and public parks. **(Zakaria and Sulieman, 2020)** examined high strength lightweight concrete with (20-80%) sawdust and 3% coconut fibers. The mechanical properties were tested under two curing conditions, including air curing (sun radiation and rain exposure) and water immersion. In general, both curing conditions maintained similar trending results. At long term curing of 180, and 365 days, specimens with 20, 35, and 50% sawdust replacement exhibited equal and/or slightly higher compressive and flexural strengths comparing to the control specimens with no sawdust and coconut fibers content. Despite using 60, and 80% sawdust replacement resulted in relatively lower mechanical properties, they still managed to reach 40 MPa of compressive strength.

(Alharishawi et al., 2020) observed no favorable performance between recycled fine and coarse particle sawdust when used as a partial replacement in lightweight concrete. Both types of sawdust caused a reduction in mechanical properties yet maintaining satisfying workability. At 28 days, the most detrimental impact was aligned with 25% sawdust replacement. The mean reduction of compressive, splitting, and flexural strength was 78.5, 46.3, and 40.6%, respectively, whereas the reported values for the control case (0% sawdust) was 24.88, 2.38, and 3.91 MPa, respectively. **(Alabduljabbar et al., 2020)** proposed a unique mix design which is cement free sawdust-based lightweight concrete. The work involved replacing cement by 30% granulated blast furnace slag and 70% fly ash, while fine/coarse aggregates were replaced at different sawdust content (0-100%). A low concentration of sodium hydroxide solution was added to activate the blend. Although the existence of sawdust by 100% content caused the compressive strength to drop from 65 to 48 MPa, the adopted mixture maintained satisfying mechanical characteristics for lightweight concrete applications. This method was also seen effective in enhancing thermal conductivity, sound absorption, and energy, besides having less carbon dioxide emissions. Further studies **(Omar et al., 2020; Dias et al., 2022)** confirmed the successful utilization of sawdust waste in reducing density (i.e., total dead load) and CO_2 release on one side and improving thermal and sound insulation on the other side. Such distinctive outcomes would ultimately serve towards environmental friendliness and better life quality. However, the inclusion of sawdust wastes without professional mix treatment (as outlined earlier) and/or with high level of replacement to natural aggregates may derive undesirable and disastrous mechanical properties **(Ugwu, 2019)**.

Table 1. Summary of related studies on normal strength concrete with sawdust content

Studies related to sawdust as partial replacement to cement							
Reference	Mix design content	Water to cement ratio w/c	Sawdust or wood waste replacement %	Research findings			
				Density (kg/m^3)	Mean compressive strength at 28 days (MPa)	Mean tensile strength (MPa)	Mean flexural strength (MPa)
(Saeed, 2013)	Cement, sand (1:1), (cement was replaced by sawdust as weight ratio) where sawdust was washed and treated with classic varnish	0.4 – 0.7	0	2217	36.1	N/D	5.13
			5	2032	33.8	N/D	5.21
			10	1873	30.0	N/D	4.94
			15	1780	25.0	N/D	4.24
			20	1652	19.6	N/D	3.57
			25	1494	14.9	N/D	3.12
			30	1383	13.7	N/D	2.81
			35	1219	6.4	N/D	1.75
(Malik et al., 2015)	Cement, sand, gravel (1:1.3:2.8), (cement was replaced by sawdust as weight ratio)	0.45	0	2447	27.55	N/D	N/D
			5	2475	32.44	N/D	N/D
			10	2437	30.22	N/D	N/D
			15	2404	22.22	N/D	N/D
			20	2370	18.66	N/D	N/D
(Awal et al., 2016)	Cement + sawdust (1:1)	0.6	--	1450	18.65	2.05	2.75
	Cement + sawdust (1:2)		--	1280	17.20	1.95	2.20
	Cement + sawdust (1:3)		--	1065	12.80	1.30	1.90
(Ikponmwosa et al., 2020)	Cement, sand, granite (1:1.8:3.7), (cement was replaced by sawdust as weight ratio)	N/D	0	N/D	25.78	2.02	N/D
		N/D	5	N/D	23.19	1.95	N/D
		N/D	10	N/D	21.93	1.73	N/D
		N/D	15	N/D	20.24	1.51	N/D

		N/D	20	N/D	18.96	1.38	N/D
(Meko and Ighalo, 2021)	Cement, sand, gravel (1:2.35:3.0), (cement was replaced by sawdust as weight ratio)	0.45	0	2920.43	31.8*	N/D	N/D
			5	2569.3	33.9*	N/D	N/D
			10	2563.9	31.0*	N/D	N/D
			15	2457.4	28.5*	N/D	N/D
			20	2450.87	25.5*	N/D	N/D
(Onyechere, 2022)	Cement, sand, gravel (1:2.58:3.42), (cement was replaced by sawdust as weight ratio)	0.57	0	2437	26.9	N/D	N/D
			5	2430	26.6	N/D	N/D
			10	2422	29.4	N/D	N/D
			20	2378	25.3	N/D	N/D
			30	2377	22.9	N/D	N/D
Studies related to sawdust as partial replacement to sand							
(Soundhirarajan and Abirami, 2018)	Cement, sand, gravel (1:1.44:3.16), (sand was replaced by sawdust (SD) and robo sand (RS) as weight ratio)	0.47	0	2647	27.78	3.18	N/D
		0.47	5 (SD) + 20 (RB)	2554	25.24	3.11	N/D
		0.47	10 (SD) + 40 (RB)	2459	21.24	2.55	N/D
		0.47	15 (SD) + 60 (RB)	2379	16.44	1.77	N/D
		0.47	20 (SD) + 80 (RB)	2296	10.58	1.36	N/D
(Oyedepo et al., 2014)	Cement, sand, gravel (1:2:4), (sand was replaced by sawdust as weight ratio)	0.65	0	2485.21	14.44	N/D	N/D
			25	2514.79	13.00	N/D	N/D
			50	2150.44	13.00	N/D	N/D
			75	2124.50	12.95	N/D	N/D
			100	2090.5	10.57	N/D	N/D
(Sawant et al., 2018)	Cement, sand, gravel (1:1.62:2.83), (sand was replaced by sawdust as weight ratio)	0.48	0	N/D	26.44	4.33	4.38
			5	N/D	21.11	3.53	2.43
			10	N/D	12.45	2.02	2.90
			15	N/D	10.07	1.13	2.36
			20	N/D	7.25	1.07	1.49
			25	N/D	5.12	0.91	1.24
(Siddique et al., 2020)	Cement, sand, gravel (1:2.08:2.46), (sand was replaced by sawdust as weight ratio) where sawdust was pre-soaked for 24 hours	0.5	0	2403	28.5	2.88	N/D
			5	2114	26.7	2.82	N/D
			10	2057	19.8	1.95	N/D
			15	1987	15.2	1.71	N/D
			20	1897	10.3	1.30	N/D
	Cement, sand, gravel (1:1.78:2.12), (sand was replaced by sawdust as weight ratio) where sawdust was pre-soaked for 24 hours	0.44	0	2413	29.8	2.94	N/D
			5	2123	27.1	2.80	N/D
			10	2073	20.1	2.08	N/D
	Cement, sand, gravel (1:1.78:2.12), (sand was replaced by sawdust as weight ratio) where sawdust was pre-treated with sodium silicate	0.44	0	2413	29.8	2.94	N/D
			5	1957	27.6	2.89	N/D
			10	1837	20.3	2.28	N/D
(Batool et al., 2021)	Cement, sand, gravel (1:2:3), (sand was replaced by sawdust as weight ratio) where concrete-sawdust was cured with sodium sulphate bath	0.45	0	2389	28.14	2.50	5.26
			10	2323	24.52	2.45	3.90
			20	2263	18.61	1.65	3.33
			30	2217	10.27	0.75	1.91
			40	2140	7.81	0.51	1.72
			50	2086	5.74	0.49	1.24
			60	1970	2.45	0.35	0.84
(Dias et al., 2022)	Cement, sand, gravel (1:1.7:2.8), (sand was	0.4	0	2303	64.27	N/D	6.6
			5	2266	63.67	N/D	N/D

	replaced by sawdust (SD) as weight ratio)		10	2229	58.97	N/D	N/D
			15	2197	57.90	N/D	5.4
	Cement, sand, gravel (1:1.7:2.8), (sand was replaced by wood chips (WC) as weight ratio)	0.4	5	2248	59.90	N/D	N/D
			10	2201	57.67	N/D	N/D
			15	2170	51.97	N/D	5.6
			20	2082	46.10	N/D	N/D
			25	2050	42.83	N/D	5.3
	Cement, sand, gravel (1:1.7:2.8), (sand was replaced by a combination of wood chips (WC) and Sawdust (SD) as weight ratio)	0.4	WD (7.5) + SD (7.5)	2223	56.47	N/D	5.3
			WD (12.5) + SD (7.5)	2130	49.03	N/D	N/D
			WD (20) + SD (5)	2057	37.73	N/D	5.0

*: tested at 7 days
N/D: no data available

4. CONCLUSIONS

A comprehensive overview was accomplished on physical and mechanical properties of building units (bricks, blocks, and concrete) incorporating sawdust wastes. Relevant studies with most prominent findings and unique mix design approaches were ascertained. The studies' remarks are articulated below:

1. Due to the lightness nature of sawdust, this characteristic offers a significant reduction in density by (10-40%) and ultimately lesser dead load structure. This feature makes sawdust an attractive solution in lightweight applications.
2. A valuable enhancement in both thermal and acoustic insulation was achieved when sawdust was added to mix samples of bricks and concrete. Depending on sawdust content, thermal conductivity can be mitigated between (10-50%) among building units. Studies also revealed a superior ability of sawdust when used to seize sound waves transmission. The porous nature of sawdust creates air pockets that trap and dissipate sound waves as they transmit through sawdust structures. All that put the efficiency of sawdust on high level of saving energy, and curbing noise pollution.
3. Adding sawdust with various quantities to the building units has profound impact of the mechanical properties. Sawdust was addressed as a partial replacement to cement or natural aggregates. Compressive strength was poorly affected by sawdust content followed by splitting and flexural strengths. However, it was possible to produce M20-25 compressive strength concrete with (5-20%) sawdust content. This assures the adequacy of sawdust utilization in structural and non-structural applications.
4. The adverse behavior in mechanical properties with sawdust was mostly attributed to the weak bond between sawdust and cement paste, the porous nature of sawdust with a high ability of water absorption and being a slow pozzolanic reaction material. To mitigate such bad influence, unique mix approaches were proposed to maintain the minimum design requirement with high sawdust content (20-50%), including boiling, washing, adding sodium silicate or sodium hydroxide solution to the blend, and curing with a sodium sulphate bath.
5. Research outcomes advocate the employment of sawdust in structural elements such as interior and exterior walls, ceilings, and non-heavy bearing load parts. This scope would pave a promising road for a less polluted environment, cost-effective construction, and proficient investment in natural resources.

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Declaration of Competing Interest

The authors declare that there is neither competing interest nor financial interest relevant to this research.

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مراجعة لاستخدام نشارة الخشب في المواد الأنشائية

ناديه غضنفر حكمت

قسم هندسة المواد، كلية الهندسة، الجامعة المستنصرية، بغداد، العراق

الخلاصة

إن انبعاثات الكاربون المصاحبة للبناء والكلفة الباهظة لمواد البناء الخام إضافة الى مخاطر ندرتها في المستقبل جميعها تهدد الاستدامة وتلحق الضرر بالبيئة. عليه، تسعى العديد من الدول برسم استراتيجيات حديثة للبيئة الخضراء من خلال اعتماد مواد معاد تدويرها وصديقة للبيئة في البناء بما في ذلك مخلفات الخشب أو نشارة الخشب. يقدم البحث الحالي مراجعة لأهم الدراسات المتميزة والطرق الواعدة المتعلقة بتوظيف نشارة الخشب في الخرسانة والطابوق. أظهرت الدراسات ذات الصلة بنجاح اضافة نشارة الخشب محل المواد الأسمنتية أو الركام الطبيعي بصورة جزئية في الخلطة الخرسانية دون حصول تأثير سلبي حاد على الخواص الفيزيائية والميكانيكية. حيث اشارت معظم الدراسات إلى أن النسبة المثلى لأستبدال السمنت أو الرمل بنشارة الخشب كانت بين (5–20%) من الحجم أو الوزن الكلي للخلطة. اما في حال تجاوزت نسبة إضافة نشارة الخشب حدود الـ (20%) فيتوجب اجراء معالجات إضافية للخلطة الحاوية على نشارة الخشب لضمان الحفاظ على الأداء والمقاومة المرغوبة. من جملة هذه المعالجات الناجعة على سبيل المثال لا الحصر، الغليان أو الغسيل الجيد لنشارة الخشب أو إضافة سيليكات الصوديوم اثناء الخلط أو الانضاج بالماء الحاوي على كبريتات الصوديوم. زيادة على ذلك، فإن الدراسات أظهرت ايضا قدرة نشارة الخشب الفعالة في تقليل الكثافة او الوزن للعينات المختبرية، وتحسين العزل الحراري والصوتي في المباني. لذا، فأن النتائج المسردة في هذه المراجعة تدعم اضافة نشارة الخشب في أجزاء البناء مثل الجدران الداخلية والخارجية، والأسقف، وأجزاء البناء الغير معرضة الى الأحمال الثقيلة. ان من شأن هذا الجانب الهام خلق فرصة لبيئة أقل تلوثًا، والمساهمة في تخفيض كلفة البناء، والاستثمار الأمثل والمستدام للموارد الطبيعية.

الكلمات المفتاحية: نشارة خشب، مواد معاد تدويرها، خرسانة خفيفة الوزن، توصيل حراري، عزل صوتي.