The Mechanical Response of Concrete Mortar Incorporating High Contents of Fine and Coarse Sawdust Particles

Nadia Ghadhanfer Hikmet
Materials Engineering Department, Engineering College, Mustansiriyah University, Baghdad, Iraq
nadiaghadhanfer@uomustansiriyah.edu.iq (corresponding author)

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ABSTRACT

This study investigates the optimal sawdust particle size distribution in mortar concrete. Two distinct replacement levels of sand with sawdust, 25% and 50%, were considered. Sawdust was initially pre-treated using bath washing, then sieved through a 2.36 mm sieve, and divided into fine and coarse sizes. For each replacement level, the mechanical properties were assessed. Findings revealed the importance of sawdust pre-treatment in maintaining concrete performance. While fine sawdust particles modified the compressive strength, coarse sawdust particles proved to be the superior for the structural applications subjected to tensile stresses. The inclusion of sawdust raised the water absorption capacity, but water absorption remained within acceptable limits. This study emphasizes the advantages of employing sawdust in construction as a sustainable approach, and low-cost alternative to sand, contributing to industrial waste reduction and eco-friendly mortar production. The study also emphasizes a proper selection to the sawdust particle size to achieve the best utilization of the material.

Keywords-sawdust; recycling; mortar concrete; treatment; sustainability

I. INTRODUCTION

Wood waste or sawdust is a major environmental issue [1]. A large amount of wood waste from industrial processes ends up in landfills or is incinerated [2, 3]. The incineration method contributes to toxic gas, like carbon dioxide, emissions [4]. The reutilization of wood wastes or sawdust in both wood-based manufacturing and construction has significantly grown. This transition has offered tangible advantages, including the low density, thermal conductivity, cost efficiency, and a comparable performance to that of raw materials [5, 6]. Sawdust waste is generated from woodworking processes, like cutting, drilling or sawing. As a result, sawdust is produced in different sizes and forms, such as powder, chips, fibers, or coarser chunks [7, 8]. Studies on sustainability have brought considerable attention to incorporating sawdust into concrete as a major and/or full replacement for some of its components. The amount of replacement is strictly determined by the component being substituted. Most studies proposed 5%-10% as the optimal degree of cement replacement with sawdust to maintain comparable performance [9-12]. Exceeding this limit deteriorates the workability and mechanical properties of concrete. This deterioration is attributed to the porous nature of sawdust, its high-water absorption capacity, and its slow pozzolanic reaction, despite containing more than 70% of a combination of SiO_2, Al_2O_3, and Fe_2O_3 in its chemical composition [13, 14]. Research has also considered on replacing fine aggregates (sand) with sawdust. Given the similarities in the chemical composition between sawdust and sand, particularly in terms of silica content, researchers had more flexibility to explore the properties of concrete production with high-percentage replacement. Authors in [15] replaced sand with 25%-100% sawdust and reported that while the compressive strength was highly affected by the excessive sawdust content (75%-100%), it was still possible to maintain an adequate performance of lightweight concrete with a sawdust content of 25%-50%. Authors in [16] investigated the mechanical properties of concrete, with natural sand being substituted by a mixture of sawdust and robo sand in varying proportions. Robo sand is defined as the dust derived from quarry stone crushing. This approach was successful in producing M20 concrete in which the fine aggregates included 50% dust waste, 10% sawdust, and 40% robo sand. Authors in [17] confirmed that 5% is the optimum sawdust replacement to keep the compressive strength above 20 MPa along with satisfying splitting and flexural strengths.

Previous research has shown the possibility to produce M20-M25 compressive strength concrete with 5%-25% sawdust content. However, some notable mix approaches have been proposed to improve the strength of concrete and have proven successful in reducing the adverse effects of sawdust. Some methods included boiling, washing, adding sodium silicate, or sodium hydroxide solution to the blend [18, 19]. In [20], the post-treatment of the sawdust-concrete was proposed, with the specimens being cured with sodium sulphate bath [20]. Such methods were able to maintain the concrete strength above 30 MPa. Other studies highlighted the significant impact of sawdust on bricks and concrete. The sawdust addition resulted in significant improvement in both the thermal and acoustic insulation [21-24], in addition to a considerable reduction in density by 10%-40%, leading to less dead load on the structure [25]. These characteristics make sawdust a promising solution in lightweight concrete applications, such as ceilings, exterior and interior walls, and non-heavy bearing load elements. Finally, the employment of sawdust in building materials enables cost-effective construction and deteriorates the environmental pollution.

Despite the research on sawdust use in construction materials, there are still gaps to be bridged. For instance, the particle size distribution of sawdust needs a detailed investigation. Fine particle sizes boost the strength leading to high-water demand and shrinkage vulnerability, while the coarse particle sizes reduce the density but create voids and weak zones. Eventually, the improper use of sawdust with an uncontrolled particle size can lead to reduced performance. Thus, the current study aims to determine the optimum sawdust particle size distribution for mortar concrete, followed by a replacement of 25% and 50% of sand by sawdust. The mixtures were then prepared with various sawdust particle sizes, ranging from fully fine or fully coarse to different combinations of both at varying percentages. The mixes were then tested for water absorption, compressive strength, splitting strength, and flexural strength.

II. EXPERIMENTAL PROGRAM

A. *Materials and Sample Preparation*

Ordinary Portland Cement (OPC) conforming to ASTM-C150: Type I was used in all mix samples. Clean local sand from Al-Ukhaidir region in Iraq was brought and sieved through 2.36 mm sieves to remove the undesired coarser particles. Sawdust wastes were collected from a local wood manufacturer and were sieved with 4.75 mm sieves to obtain a consistent and compatible composition to the sand and remove any unwanted particles. Sieving is important to avoid the flakiness associated with sawdust wastes larger than 4.75 mm. The sawdust waste was from a type of wood called “Cham,” which originates from North America. The second stage of sawdust sieving was aimed at separating the fine from the coarse particles. This was accomplished by sieving through a 2.36 mm sieve, with the retained particles, mostly of flake or fibrous form being labeled as coarse particles. To improve the interaction and matrix bond between the sawdust and other materials, both types of sawdust were washed, then rinsed and kept under sunlight for a couple of hours, as seen in Figure 1. Washing was required to remove any attached impurities, such as harmful sulphate and silt sediment along with reducing the water absorption tendency. This method has been previously proposed and was found effective in enhancing the matrix bond and mechanical response [18]. The chemical and physical properties of cement, sand, and sawdust are presented in Table I.

B. *Mixing and Casting*

Prior to mixing, steel molds were cleaned and lubricated to facilitate an easy separation of the specimens after hardening. Cubes measuring 50 mm × 50 mm × 50 mm were used for the sample compression and water absorption tests, while 50 mm × 100 mm cylinders were used for the splitting test. Finally, 40 mm× 40 mm× 160 mm prisms were casted for the flexural test. Meanwhile, materials were separately weighed according to the required mix design and prepared for mixing. Initially, a control mortar concrete mixture with a design compressive strength of 20 MPa was prepared. The cement/sand ratio by weight was 1:3, whilst the water/cement ratio was 40%. The mixtures with sawdust were prepared in two ways: with 25% sand replaced by sawdust and with 50% sand replaced by sawdust.

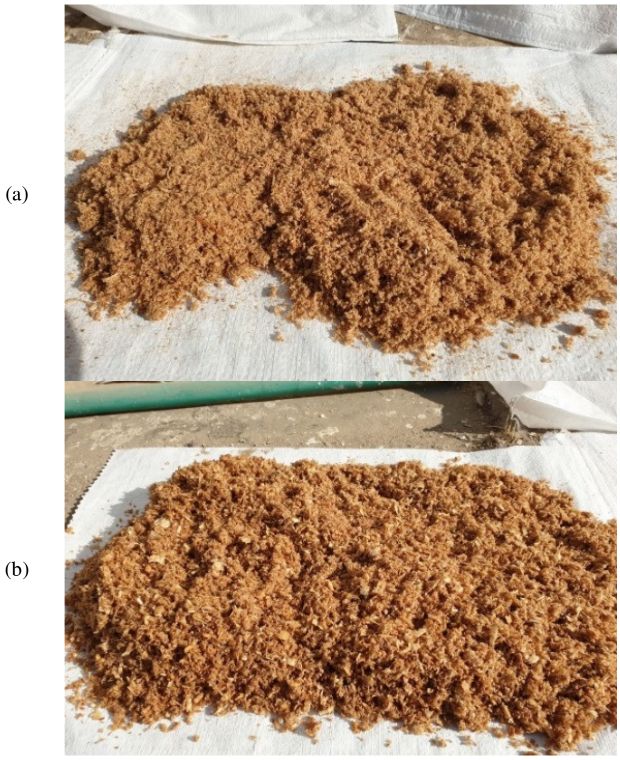

Fig. 1. Sawdust exposed to sunlight after being treated: (a) fine, (b) coarse.

For each replacement, the samples were further subdivided into five categories based on the sawdust particle size ratio as 100% fine (Full F.SD), 100% coarse (Full C.SD), 50% coarse and 50% fine (1 C.SD: 1 F.SD), 75% coarse and 25% fine (3 C.SD: 1 F.SD), 25% coarse and 75% fine (1 C.SD: 3 F.SD). Table II presents the mix proportions of the laboratory experiment. The mixing of cement and sand was carried out in a controlled laboratory environment (25°C-30°C). Sawdust was added and manually mixed until a uniform mixture was achieved. Finally, water was gradually poured and the mixing continued until a homogenous fresh mortar-concrete was obtained. The fresh mixes were poured into steel molds. After 24 h, the hardened specimens were demolded and cured in water at room temperature for 28 days. Figure 2 shows the fresh mortar-concrete during mixing and mold casting. On the day of testing, the specimens were taken out from the curing tank and their surfaces were dried using a rag. It should be noted that the average of three specimens' results is reported.

III. RESULTS AND DISCUSSION

A. Compressive Strength

The compressive strength test was carried out in accordance with BS 1881-116 [26], using a hydraulic compression machine, as shown in Figure 3, with an ultimate capacity of 300 kN. The load was steadily applied with a slow rate of 1 kN/sec until failure. The corresponding compressive strengths of all groups are given in Table III. Initially, the control specimens sufficiently met the design target, with a recorded strength of 21.62 MPa, which confirms the mix design. Contrary to expectations, the addition of 25% sawdust showed comparable performance with the control specimen. This outstanding outcome is attributed to the pre-treatment of sawdust in which impurities were removed, and the effective mixing, resulting in high workability and matrix bond formation. The presence of oxide compositions in sawdust, as presented in Table I, played a major role in enhancing the pozzolanic activity of the mixes. Having a considerable amount of calcium oxide (CaO) was a key element in boosting the strength and durability of hardened mixes by reacting with silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3) [27]. Figure 4 illustrates the compressive strength results obtained with 25% sawdust replacement compared to the control case. It is evident that the addition of fine sawdust (M2: Full F.SD. M5: 1 C.SD.: 3 F.SD.) produced the most favorable results compared to the major and/or full addition of coarse sawdust. Fine particle sizes are superior in filling voids, which results in higher strength to resist the applied forces.

TABLE I. CHEMICAL AND PHYSICAL PROPERTIES OF MATERIALS

Chemical properties					
Cement		**Sand**		**Sawdust**	
CaO	61.06%	SiO_2	79.62%	K_2O	18.646%
SiO_2	17.62%	Al_2O_3	3.34%	Fe_2O_3	4.683%
Al_2O_3	4.92%	Fe_2O_3	1.85%	TiO_2	0.573%
Fe_2O_3	3.06%	CaO	4.45%	MnO	0.469%
MgO	1.62%	SO_3	4.81%	CuO	0.122%
SO_3	2.47%	MgO	1.52%	ZnO	0.050%
C_3A	7.86%	K_2O	1.76%	SrO	0.028%
L.S.F.	1.39%	Na_2O	1.93%	Al_2O_3	2.460%
		TiO_2	0.72%	CaO	22.220%
				Cl	0.010%
				SO_3	5.920%
				SiO_2	44.730%
				MgO	0.090%
Physical properties					
Cement		**Sand**		**Sawdust**	
Specific gravity	3.15	Specific gravity	2.65	Specific gravity	0.36
Fineness modulus	-	Fineness modulus	2.52	Fineness modulus	2.45

TABLE II. MIX PROPORTIONS

Mix series	Cement (kg/m^3)	Sand (kg/m^3)	Water (L/m^3)	Sawdust (kg/m^3)	Sawdust %	Sawdust details
M0	1250	3975	490	0	0	No-sawdust
M1	1250	2980	490	138	25%	Full C.SD.
M2	1250	2980	490	138	25%	Full F.SD.
M3	1250	2980	490	138	25%	1 C.SD.: 1 F.SD.
M4	1250	2980	490	138	25%	3 C.SD.: 1 F.SD.
M5	1250	2980	490	138	25%	1 C.SD.: 3 F.SD.
M6	1250	1987	490	275	50%	Full C.SD.
M7	1250	1987	490	275	50%	Full F.SD.
M8	1250	1987	490	275	50%	1 C.SD.: 1 F.SD.
M9	1250	1987	490	275	50%	3 C.SD.: 1 F.SD.
M10	1250	1987	490	275	50%	1 C.SD.: 3 F.SD.

C.SD.: Coarse Sawdust, F.SD.: Fine Sawdust

TABLE III. TEST RESULTS OF MIXTURES

Mix series	Mix description	Compressive strength (MPa)	Splitting tensile strength (MPa)	Flexural strength (MPa)	Water absorption (%)	Dry density (kg/m^3)
M0	No-sawdust	21.62	2.55	3.57	4.5	2050
M1	Full C.SD.	20.57	2.48	3.24	5.8	1934
M2	Full F.SD.	23.30	2.13	2.58	6.4	1942
M3	1 C.SD.: 1 F.SD.	20.63	2.25	2.65	5.7	1915
M4	3 C.SD.: 1 F.SD.	19.47	2.43	3.1	5.9	1926
M5	1 C.SD.: 3 F.SD.	22.69	2.23	2.62	6.2	1938
M6	Full C.SD.	13.89	2.11	2.46	6.5	1758
M7	Full F.SD.	17.90	1.50	1.62	7.6	1769
M8	1 C.SD.: 1 F.SD.	17.49	1.94	2.16	6.8	1765
M9	3 C.SD.: 1 F.SD.	16.61	2.02	2.35	6.5	1760

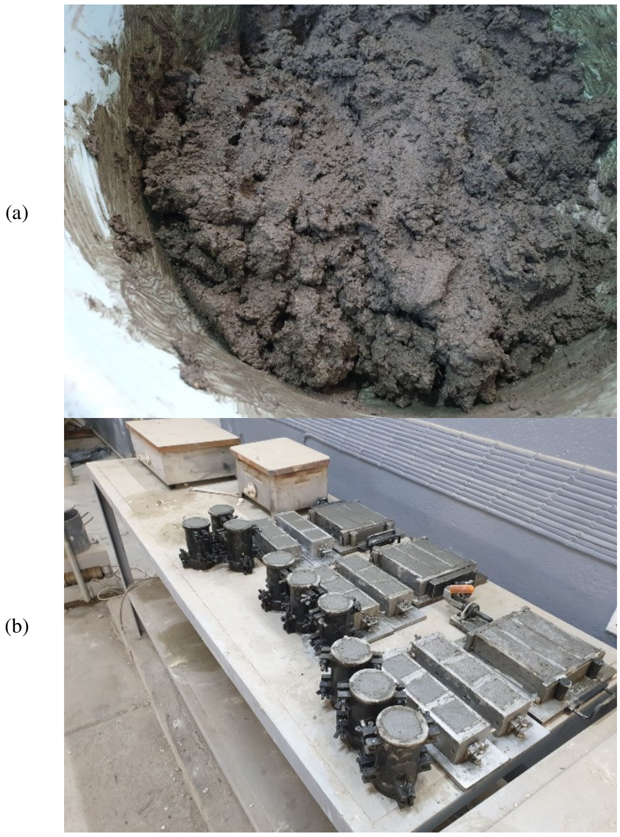

Fig. 2. (a) Sample of fresh mortar-concrete mixture, (b) mold casting.

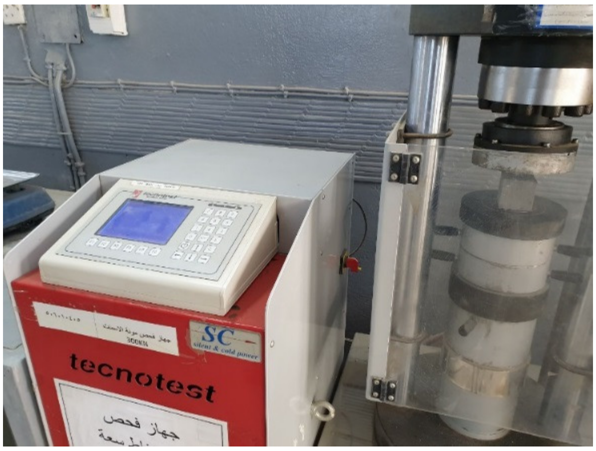

Fig. 3. Compressive strength testing machine.

Based on the compressive test results, it was concluded that to achieve the maximum performance of the sawdust mortar-concrete, it is essential to use finer particle sizes as a major and /or full content in mixes. Similar trends were reported with 50% sawdust replacement level, except that the compressive strengths were below the design target in all cases. Figure 5 portrays the compressive strengths of these specimens compared to the control case. In general, the drop in the compressive strength with 50% sawdust can be attributed to the sawdust agglomeration associated with poor matrix bond.

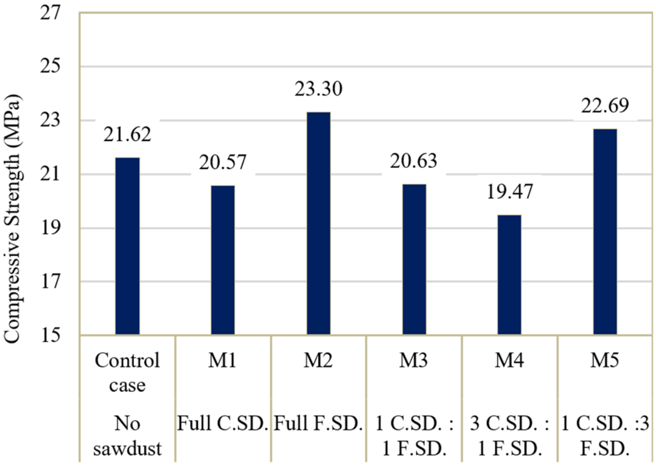

Fig. 4. Compressive strength for tests with 25% sawdust replacement.

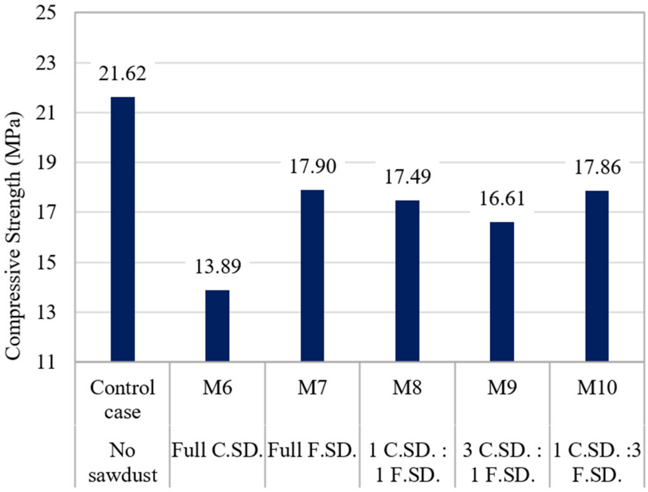

Fig. 5. Compressive strength among tests with 50% sawdust replacement level.

Using coarse sawdust as the full content (100%) sharply reduced the strength of the mixes, specifically for the specimen with 50% sawdust replacement level. The findings revealed a 36% decline in the compressive strength compared to the control case. This decline was significantly reduced when fine sawdust was added to the mix (M8: 1 C.SD.: 1 F.SD.) and (M10: 1 C.SD.: 3 F.SD.), or when complete fine sawdust was utilized (M7: Full F.SD.). The fine particle sizes of the sawdust have a smaller surface area which acts as a filler material and they are better coated with cementitious materials, leading to an overall robust matrix bond against the compressive stresses. The current outcomes favor the use of sawdust in concrete mortar application up to a 25% replacement level to sand if the sawdust is pre-treated. Moreover, it was found that the coarse particles of sawdust lead to a severe drop in performance, while the fine particles are an ideal choice for structural elements subjected to compressive stresses.

B. Splitting Tensile Strength

The splitting tensile strength test was performed in accordance with ASTM C496 [28]. The cylindrical specimens were horizontally positioned and subjected to a uniformly pressure along their longitudinal axes until failure, as shown in Figure 6. The results were calculated using:

$$f_t = \frac{2P}{\pi DL} \tag{1}$$

where f_t is the split tensile strength in MPa, P is the maximum recorded load at failure in N, D is diameter of the cylindrical specimen in mm, and L is length of the cylindrical specimen in mm.

The average tensile strength of three cylindrical specimens of each mixture are reported in Table III. The results indicate a general decline in the split tensile strength for a 25% sawdust replacement level compared to the control case (M0). However, the decline is more significant in mixtures with a major and/or full addition of fine sawdust (M2: Full F.SD., M5: 1 C.SD.: 3 F.SD.). The decrease was 17% and 13%, respectively. The reduction in split tensile strength was also associated with the major and/or full presence of coarse particle sizes of sawdust. Such a drop was marginal, counting for 3% and 5% for specimen M1: Full C.SD., and M4: 3 C.SD.: 1 F.SD., respectively. The same trends were observed with mixtures incorporating a 50% sawdust replacement, but, the decline in split tensile strength was more significant. As compared to the control case, the mixtures with major and/or full addition of fine sawdust (M7: Full F.SD., M10: 1 C.SD.: 3 F.SD.) showed a decrease of 41% and 24%, respectively. On the other hand, the mixtures with a major and/or full addition of coarse sawdust particle (M6: Full C.SD., M9: 3 C.SD.: 1 F.SD.) showed a decline in the split tensile strength up to 17% and 21%, respectively.

Fig. 6. Splitting tensile strength test.

Figure 7 illustrates the influence of the sand replacement by sawdust on the split tensile strength. In general, the addition of sawdust into the mortar concrete decreases the split tensile strength. This is attributed to the poor bond between the sawdust and cement paste. Authors in [29] presumed that the sawdust particles formed heterogeneous discontinuities in the cementitious matrix. Eventually, a weaker transition zone is formed, trigging cracks to be initiated at an early stage of loading [30, 31]. Nevertheless, the split tensile performance of the mixtures with major and/or full coarse sawdust content was found to be less adverse than that of the mixtures with a major and/or full fine sawdust content. This discrepancy could be due to coarse sawdust particles behaving as a reinforcing component, which bridges the transition zone and stops the crack formation. This outcome emphasizes the necessity of a careful selection of sawdust particle sizes prior to use. Furthermore, it could be concluded that the addition of coarse sawdust is a favorable solution to the structural elements subjected to tensile stresses.

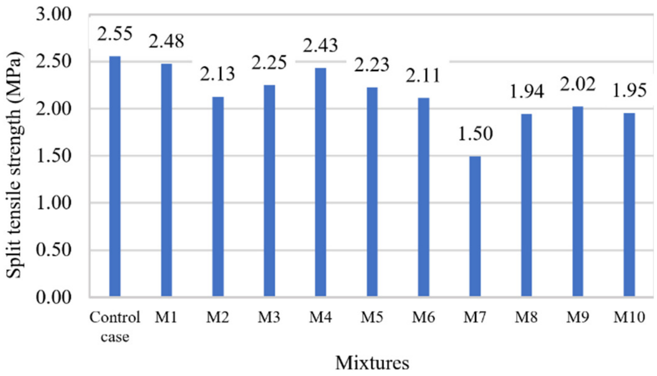

Fig. 7. Split tensile strength results.

C. *Flexural Strength*

This test was conducted in accordance with ASTM C293 [32]. The prismatic specimens of 40 mm 40 mm × 160 mm dimensions were tested under a one-point loading machine, as shown in Figure 8. The flexural strength was calculated using (2), and the average of three results for each mixture was then determined and reported in Table III:

$$f_l = \frac{P\times L}{b\,d^2} \tag{2}$$

where P is the maximum recorded load at failure in N, L is the effective span of the prism (center-to-center) in mm, b is the breadth of the prism in mm, and d is the height of the prism in mm.

Fig. 8. Flexural strength test.

Figure 9 presents a comparison of the flexural strengths of the mixtures. The flexural strength of the control mixture (M0: no-sawdust) was 3.57 MPa. For the mixtures with a 25% sawdust replacement level (M2: Full F.SD., M5: 1 C.SD.: 3 F.SD.), there was a significant decline in the flexural strength. This reduction was associated with the major and/or full addition of fine sawdust particles, yielding flexural strengths of 2.58 MPa and 2.62 MPa, respectively. In contrast, the presence of coarse particle sizes of sawdust in the mixtures (M1: Full C.SD., M4: 3 C.SD.: 1 F.SD.) resulted in less flexural strengths, measuring 3.24 and 3.10 MPa, respectively.

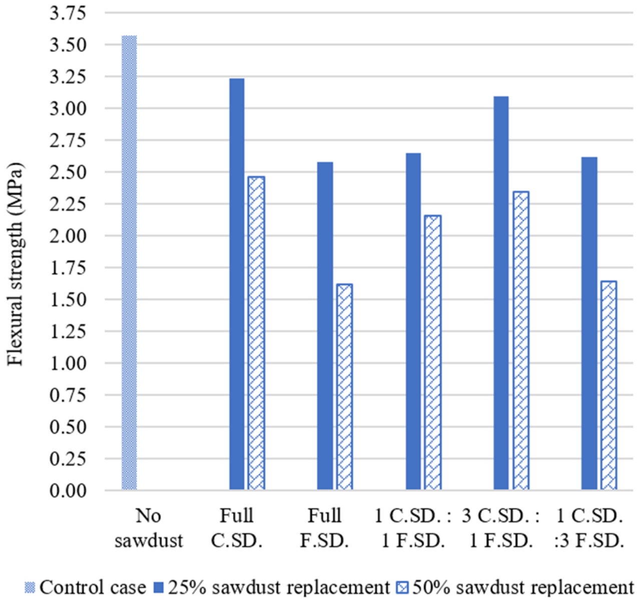

Fig. 9. Flexural strength results.

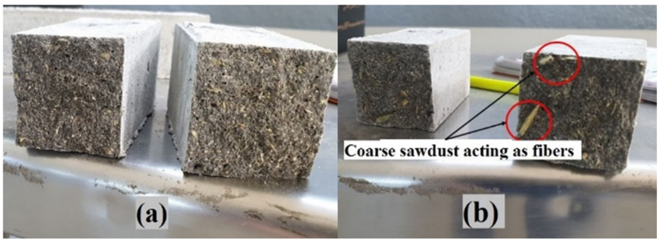

Fig. 10. Cross-section view of prisms after failure: (a) with fine sawdust, (b) with coarse sawdust.

Similar trends were observed with the mixtures having a 50% sawdust replacement. Mixtures with fine sawdust as a major and/or full component (M7: Full F.SD., M10: 1 C.SD.: 3 F.SD.) resulted in a drastic reduction in the flexural strength by 55% and 54%, respectively, as compared to the control mixture. This severe decline was reduced when the major and/or full component of sawdust was replaced with coarse particle sizes (M6: Full C.SD., M9: 3 C.SD.: 1 F.SD.), resulting in 31% and 35% decline compared to the control mixture. To understand this behavior, a visual analysis was conducted on the inner faces of selected prisms at the location of flexural cracks. From Figure 10, it is evident that the superior performance of the flexural strength that is associated with the use of coarse sawdust, compared to the fine sawdust, is due to the coarse particles acting as fibers along the crack transition zone. For this reason, a proper selection of the particle size of sawdust is proposed to achieve the efficient use of the material.

D. Water Absorption Test

The water absorption for all mixtures is calculated with (3). The average of three test results for each mixture was determined and the results are presented in Table III:

$$Water\ absorption\ (\%) = \frac{W_W - W_D}{W_D} \times 100 \qquad (3)$$

where W_W is the wet weight of the sample after being immersed into water (gm) and W_D is the dry weight of the sample (gm).

For the control case, the water absorption was 4.5%, which is below 10%, the maximum allowable limit proposed by most design guidelines and studies [33]. For the mixtures with a 25% sawdust replacement, it was observed that the water absorption for all mixtures irrespective of their particle size of sawdust was slightly higher than the control case, with a maximum value of 6.4%, below the 10% limit. Finally, for the mixtures with 50% sawdust replacement, the water absorption was higher than the control case, as expected. However, all results satisfactorily met the maximum allowable limit, with an the maximum value being 7.6%. Generally, sawdust has a high water absorption capacity and retains water due to its porous nature. This property of sawdust significantly deteriorates the mechanical properties of concrete, unless there are treatment processes to mitigate it [34]. Such processes include coating sawdust with waterproofing materials or using sawdust in a surface saturated dry condition [18, 19]. The latter treatment was adopted in the current study and proved effective in maintaining the water absorption capacity within an acceptable range. Overall, a careful use of the sawdust waste with proper moisture content checks is proposed to produce a durable sawdust concrete mixture.

IV. CONCLUSIONS

The current research assesses the optimum sawdust particle size distribution for mortar concrete. The mix design involves a high content of sawdust with 25% and 50% replacement levels of sand. For each replacement level, the sawdust wastes were sieved through a 2.36 mm sieve and designated as fully fine, coarse sizes, and a combination of both at different proportions. The mechanical properties including the compressive strength, splitting tensile strength, flexural strength, and water absorption were evaluated. The key findings of the study are:

- Mortar-concrete with sawdust has unfavorable mechanical properties, unless the sawdust is pre-treated. In this research, the sawdust was pre-treated with bath washing and rinsing. This simple and cost-effective process removed the impurities and unwanted particles, which reflected positively on the mechanical properties.
- The findings suggest that the compressive strength is a function of the fine particle sizes of sawdust. The mixtures with full fine particles and/or predominant (1 C.SD.: 3 F.SD.) fine content of sawdust provided the most favorable and comparable performance compared to the control case (no-sawdust).
- Due to the fiber action of the coarse particle size of sawdust, both splitting tensile and flexural strengths obtained with mixtures of full and/or predominant coarse

particles (3 C.SD.: 1 F.SD.) were higher than that of the mixtures having a fine sawdust as their major component. It was concluded that the coarse sawdust is a favorable solution to the structural elements subjected to tensile stresses.

- The addition of sawdust into the concrete mixtures increases the water absorption capacity in all cases irrespective to the particle size or sawdust replacement level, compared to the control case. The highest water absorption was at 7.6% for the mixture with a 50% sawdust replacement level. However, these increments remained below the maximum allowable limit of 10%. This success can be attributed to the use of sawdust in a surface saturated dry condition during mixing, which enabled the moisture level to be stopped at a balance range.
- This research sheds the light on the sustainability and recycling by using a cheaper and abundant material, like sawdust, as a partial replacement of sand in concrete. This approach serves towards more cost-effective buildings and eco-friendly mortar production.

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