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Development of Wood-Crete from Hardwood and Softwood Sawdust

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Abstract: Wood-crete, a new building material has previously been developed from sawdust, inorganic binder and addition of waste paper, finding its use mainly for wall panelling or other non- and semi-structural applications with good thermal insulating properties.

In this study, the properties of wood-crete were investigated based on the type of wood sawdust – hardwood (beech and oak) and softwood (pine and cedar). The results showed that (1) the compressive strength of wood-crete was closely related to the wood species, with the compressive strength of 3.93MPa being for hardwood wood-crete compared to 1.37MPa and 0.26MPa of wood-crete from softwood and mixed wood respectively; (2) wood-crete from hardwood sawdust had a higher density than those made from softwood sawdust and mixed wood; (3) particle size had a significant influence on the strength properties and density of wood-crete with wood-crete made from 1mm particle size recording a higher compressive strength and density compared to 2mm and 3mm particle size. The optimum size for wood-crete was dependent on the wood species; (4) thermal conductivity of wood-crete was closely related to the chemical composition of various wood species, with softwood wood-crete having about 20% lower thermal conductivity compared to hardwood wood-crete; (5) a ratio of 1:2 of sawdust to binder was found advisable for the production of wood-crete for various wood species and particle sizes investigated. The compressive strength of wood-crete made from sawdust of both softwood and hardwood was similar to or higher than that of hempcrete, indicating their suitability for wall panelling or other non- and semi-structural applications. The results of this study provide an important foundation for choosing what wood species, particle sizes and combinations of sawdust to be used for the production of wood-crete.

Keywords: Wood-crete, tradical lime, sawdust, compressive strength, wood species, thermal conductivity.

1. INTRODUCTION

Wood-Crete is a new material made from sawdust or other wood wastes, and Tradical lime with consideration for low cost and locally available materials to meet desired needs, enhancing self-efficiency and leading to an overall reduction in construction cost for sustainable development. Wood-crete from different hard and soft wood is being developed in this study, intending to achieve similar properties to those of wood-crete in previous study [1] but most importantly to determine the different specific wood properties posed on strength properties of wood-crete. Wood waste, a major constituent of wood-crete, may be sawdust from the sawing of softwood or hardwood, or any other softwood and hardwood wastes (for instance, wood chips). Since wood is used in large quantities in many different sectors and is a part of our everyday lives, the volumes of sawdust and other recovered wood available are also large. Sawdust could be loose particles or wood chippings obtained as by-products from sawing of timber into standard useable sizes.

Wood-crete as developed in previous study [1] is intended to achieve similar properties but more cost effective as those of Hempcrete. The term used for the light weight, insulating and breathable material produced after mixing Hemp shive with a lime based binder and water is known as hempcrete [1]. Its use involves casting it around a load bearing frame (such as a timber frame) within temporary formwork or can be spray applied.

Sawdust has been used in combination with inorganic binders to produce wood-cement composites replacing sand and aggregate in concrete mix. There are a number of merits offered by wood and inorganic binders over some conventional building materials presently used. These composites combine the properties of both the wood fibre and matrix, which makes them more valuable to the building industry. Inorganic wood composite, such as wood-cement composite, has been studied in a great detail. It has been reported that the properties of wood-cement composites are dependent on wood species and other processing parameters (e.g. Blankenhorn *et al.*) [2]: (1) as hydration time increased, the compressive strength of wood-cement composite increased; (2) mild chemical modification could provide some improvements in the compressive strength values for acetic acid and sodium hydroxide wood-cement composites compared to unmodified composites; (3) as the cement-to-wood ratio decreased, the compressive strength of the wood-cement composite decreased; (4) the effects of chemical modification on compressive strength depended on the hardwood species. Hardwoods have also been reported to have a lower compatibility with cement than softwood, partly due to the inhibitory properties of hydrolysable hemicellulose and other extractives present in hardwoods [3]. Experimentation with a group of four hardwoods and five softwoods from North America [4] revealed that hardwoods adversely affected ten-

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sile strength and exothermic behaviour of cement more than softwood.

Additionally, it has been reported that various chemical components of different wood species affects wood-cement composites [5]. Lignin has been reported to yield high performance concrete strength, set retarder for a cement composition and improve the compressive strength of cement pastes [6]. Furthermore, it has also been stated by Pourchez *et al.* (2006) [7] that cellulose retards cement hydration process. The effect of cellulose is attributed to the increased viscosity of the water, which imparts the movement of ions, decreasing the dissolution rate of anhydrous phases and the precipitation of hydrates [7]. Likewise, it has been reported that water-soluble extractives of wood (hemicelluloses, starch, sugar, tannins, certain phenols and even lignin) can retard and sometimes inhibit the normal setting and strength development properties of cement during the production of wood/cement composites [8].

This study was to investigate the effect of wood species and other relevant experimental parameters on the properties of wood-crete. The composition and hence quality of sawdust may vary considerably from one to another resource, even of pure softwood or hardwood or a combination of various percentages of hardwood and softwood or various wood species within softwood and hardwood. A better understanding of raw materials and related influence on wood-crete production is highly desirable for the development of this new construction material.

2. MATERIALS AND METHODS

2.1. Materials

Table **1** show materials used for the production of wood-crete which includes sawdust, binder (tradical lime) and water including their composition and weight. Sawdust and binder were mixed in ratios 1:2.

Table 1. Material Composition and Weight

Materials		Density (kg/m3)	Weight
Sawdust	Cedar	530	120g
	Pine	510	
	Oak	750	
	Beech	730	
Tradical lime		1201	240g
Water		1000	450ml

2.1.1. Hardwood and Softwood

Softwood chosen for this study is pine and cedar. Pine sawdust was chosen due to its resistance to shrinkage and swelling [9]. Sawdust from cedar wood was chosen due to high shock resistance [9], good dimensional stability and pleasant scent of the wood which acts as a natural insect repellent which can add natural properties to wood-crete blocks [9].

Hardwood chosen for this study includes oak and beech. Oak wood was chosen for this study due to its common use for making furniture which leads to high availability of sawdust from sawmills. As well, oak wood is known for great strength and hardness, and is very resistant to insect and fungal attack because of its high tannin content. Beech wood sawdust was chosen as a result of good strength properties, abrasion resistance and high in resistance to shock associated with beech wood [9]. In general, oak wood and beech wood are the most used type of wood in production of furniture in European markets [10] which makes them well known and popular in sawmills. Other parameters of wood species used in this study are summarised in (Table **2**) while the strength values of other building materials are stated in (Table **3**).

Table 2. Composition of Different Wood Species

	Beech	Oak	Pine	Cedar
Density (kg/m3)	730	750	510	530
Cellulose (%)	44.0	42.0	44.0	45.0
Hemicellulose (%)	24.5	29.0	28.5	13.2
Lignin (%)	22.4	25.0	28.1	29.3
Extractives (%)	2.0	4.4	3.8	10.2
Ash (%)	0.3	0.3	0.4	0.2

2.1.2. Binder

The binder used for wood-crete production is tradical lime. Tradical lime is also referred to as pure air lime which fulfills the qualities of fineness and reactivity. Tradical lime binder is a substance that sets and hardens independently and can bind other materials together. They have been used in the production of tradical hemp lime products for natural high performing and sustainable construction materials. Tradical lime hardens due to hydration and hardens even underwater or when constantly exposed to wet weather. Tradical lime is used in the production of mortars used for building masonry, for rendering or plastering, for decorating in both renovation and new build constructions. Tradical lime is known for its elasticity, durability (long lasting quality mortars), workability, vapour permeability and healthy material (natural and solvent-free).

2.2. Method

The manufacturing of wood-crete from specific sawdust followed the same process as described in previous work [1]. This involved the mixing of binder (tradical lime) with sawdust. The process involved measuring the required amount of sawdust needed and binder at the designed ratios. The ratios of sawdust to tradical lime used were based on economic considerations and permissible impact on the strength ascertained using the dropping method, as explained by Zziwa, *et al.* 2006 [11], where preliminary trial specimens of varying compositions of sawdust and cement were made, dried and dropped from waist height (approximately 1m) to assess their structural integrity.

Table 3. Material Properties of Lime-Hemp Concrete and Some Other Building Materials

Material	Young Modulus (MPa)	Compressive Strength (MPa)	Density (kg/m^3)	Thermal Conductivity ($W/M.^0C$)
Steel	210000	350-1000	7500-8500	52.00
Concrete	20000	12-80	20000	1.50
Cellular Concrete	1000-2500	5	420-1250	0.14-0.23
Brick	10000-25000	25 – 60	1300-1700	0.27-0.96
Wood	230–20000	4 – 34	350-900	0.12-0.3
Lime Hempcrete	24	0.4	445	0.17

Table **4** shows the trial making used to determine the workable mix ratio of water to lime. During trial making, the mix made with water to total mix weight less than 450ml was found unworkable while the trial mix of water above 450ml was found to be slurry. Only the mix with the amount of water of 450ml for every 360g of total mix weight was found workable. Therefore, this ratio is termed as the mix workability ratio.

Table 4. Mix Ratio in Trial Making

Water (ml)	Total mix weight (g)	Workable mix
300	360	No
400	360	No
500	360	Yes (slurry)
480	360	Yes (Slurry)
450	360	Yes

The mix ratio developed is also important to ensure individual wood particles to be fully encased by the binder to attain acceptable properties. Sawdust and binder (tradical lime) were mixed together before the addition of water so as to attain consistency in the mix. Consistent and uniform mixing was carried out to allow for clumps to be broken down and binding powder (tradical lime) to be dispersed evenly throughout the sawdust. Continuous mixing was done for a further few minutes after the addition of all materials in the mix. The mix was then uniformly distributed into the square moulds which were treated with a mould release agent. Preparation of specimens for testing strength properties was based on BS EN12390-2 [12] (making and curing specimens for strength tests). Wood-crete blocks were moulded in the dimension of 100mm x 100mm x 100mm. It was noticed that due to the light weight of sawdust, there was almost no compaction under self-weight, hence the tendency to create larger voids in moulds which could lead to low density and low strength. For each mix combination, three replicates were made for each sawdust to tradical lime of ratios 1:2 and ratio 1:1. A total of 72 samples were made. Of significant note is that the degree of compaction has a great impact on the density of wood-crete. In a bid to ensure equal compaction in the mould, a minimum of eight tamps was performed on each mould with minor force before levelling. The importance and advantage of tamping help remove voids and fill gaps whilst creating a consistent end product. The mixtures were placed in a forming mould for 24 hours to allow for setting before de-moulding while maintaining a relative humidity between 46% and 49% for all samples. The setting of inorganic binders is the result of a series of chemical reactions causing a succession of crystallisation stages [13]. The samples were left at open air cure in the lab for 32 days to attain the required amount of strength before being subjected to various kinds of tests.

2.3. Testing

Prior to testing, the actual volume of the blocks was taken from the measurement of samples after drying. Samples were sandpapered for evenness and flatness in all sides while sample mass was determined using a weighing scale. The density of the blocks was calculated from mass and volume. Three replicates were taken for each type of wood-crete block.

Wood-crete blocks were tested for compressive strength at 20°C/65% relative humidity by applying a gradually increasing load under a universal Instron. The test pieces were placed between a supporting base and a flat steel plate. The machine applied a uniform load at a rate of 6mm/min until the maximum failure load was reached. The maximum load (in Newton) was automatically recorded and the compressive strength was calculated as maximum failure stress per unit area.

Thermal conductivity was tested for various wood-species to investigate the difference in thermal conductivity of wood-crete made from both hardwood and softwoods. The thermal conductivity was determined by using Isomet Thermal Conductivity analyser. A sensor is placed on a sample which produces an amount of heat on application of current (Fig. **1**). The heat provided results in a rise in temperature at the interface between the sensor and the sample. Both thermal conductivity and effusivity are measured directly and rapidly, providing a detailed overview of the thermal characteristics of the sample material. The results are then displayed on the system's computer. Thermal effusivity is a measure of a materials ability to exchange thermal energy with its surrounding while thermal conductivity is the ability of a material to conduct heat.

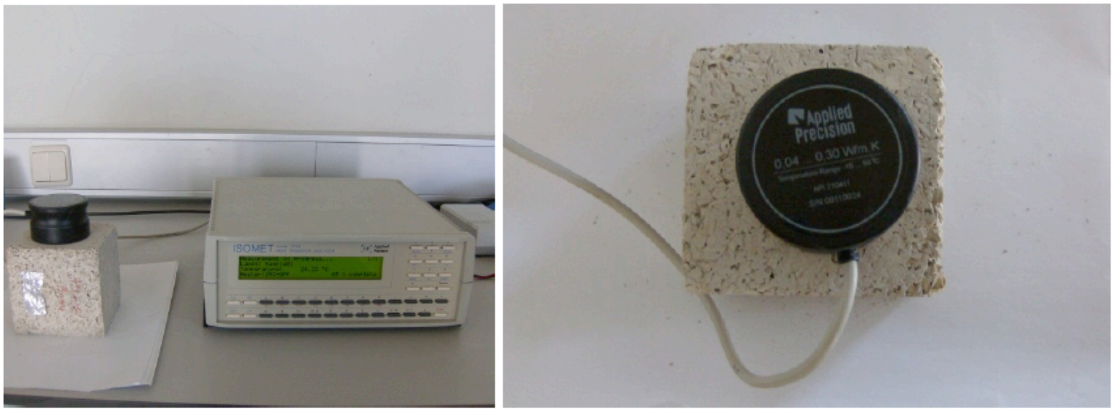


Fig. (1). Thermal conductivity test.

3. RESULTS AND DISCUSSION

3.1. Correlation of Density and Wood Species (Sawdust)

An important factor for the difference in densities of wood-crete composites is due to individual wood densities of hardwood and softwood and their composition (Table **5**). The effect of wood density on the density of wood-crete may result from two different aspects: one is the density of wood itself as a higher density means that more amount of wood and cell materials per unit volume to the wood sawdust within the wood-crete made; the other is the structure of wood. The density of wood is in general related to wood anatomy and hence the relative proportions of cell types or tissues most especially in hardwood species (vessel, fibre, axial and radial parenchyma), along with also their dimensions and distribution, which have indications of the penetration and setting of the lime matrix [5]. The level of effect is dependent on the balance of effects between the former and the latter. In this study, the density of most hardwoods is higher than softwoods naturally and this was reflected in the density of wood-crete with the blocks made from hardwood sawdust recording an 18% increase when compared to the density of wood-crete blocks made from softwoods. Research however shows that most hardwoods have less air in them than softwoods which also affects wood density [14, 15].

Furthermore, it was also noticed during wood-crete manufacturing that the softwood sawdust was lighter in texture than those of hardwood which made compaction in the mould more difficult than when using sawdust from hardwood which was finer and dense thus making compaction more compact. Wood-crete made from the mixed wood sawdust showed 18% reduction in density compared to wood-crete made from hardwood and 0.08% increase in density compared to wood-crete made from softwood (Table **5**). The term mixed sawdust refers to wood waste from the sawing of wood of various types of both soft and hard woods without making reference to the percentage of hardwood or softwood in the mix. It is important to make use of this type of wood waste because in reality, sawmills do not separate their wood waste by wood species or wood type. Much more reduction in density compared to hardwood blocks and only slight increase in density compared to softwood blocks infers that the composition of the mixed wood sawdust may contain more softwood than hardwood, or the composition of the mixed wood may result in 'bridging' due to the different stiffness between hardwood and softwood. Fig. (**2**) also shows that density of wood-crete made from hardwood beech is 5.7% higher than density of wood-crete made from hardwood oak, likewise density of wood-crete from softwood pine is 10.3% higher than density of wood-crete made from softwood cedar. The highest density of wood-crete made in this study is about 70% higher than the lowest one (Table **5**), showing a significant effect of wood species for the production of wood-crete (Table **2**).

3.2. Correlation of Compressive Strength and Wood Species

Fig. (**3**) shows the correlation of compressive strength and wood species. It can be seen that the compressive strength of wood-crete beech is 29.1% higher than the compressive strength of oak and compressive strength of wood-crete pine is 79.3% higher than the compressive strength of wood-crete cedar. Overall, wood-crete made from hardwood had a much higher compressive strength than wood-crete made from softwood, on average 60.2% higher for the former compared to the latter. This may be due partly to the difference in the density (17.5%) between hardwood and softwood. A higher density of wood generally gives rise to a higher compressive strength and such the wood-crete would have a higher compressive strength due to the contribution of wood itself. It has also been reported that hardwoods are usually strong in compression, tension and shear while softwoods are strong in tension but weak in shear [15]. However, softwoods are generally strong along the grains while hardwoods are strong both along and across the grains. This difference may also contribute to the higher compressive strength of hardwood wood-crete made.

The property of composite is in general closely related to its density because the higher density means more compaction of the composite. In order to determine the degree of compression of wood-crete made with various densities of wood species, i.e. hardwood and softwood species in this study, it is necessary to calibrate the density of blocks by taking into account the ratio of mix of wood-crete and the densities of individual wood species used in this study which include beech, oak, pine and cedar. The percentage of tradical lime was two-third in mix while sawdust was one-third in mix. The density of tradical lime is 1201kg/m3. Therefore, the calibrated density of wood-crete = 1201 (2/3) + ρ (1/3)

Table 5. Mean Density and Compressive Strength of Wood-Crete with Experimental Mixture Design

Samples		Particle size (mm)	Compressive strength (MPa)	Density (Kg/m3)
Hardwood				
HW_B	Beech	1	3.93 (8.4)	934
		2	3.90 (7.0)	926
		3	3.44 (6.9)	929
HW_O	Oak	1	2.19 (3.7)	859
		2	2.07 (10.1)	821
		3	1.95 (9.2)	816
Softwood				
SW_P	Pine	1	1.37 (6.8)	696
		2	1.30 (4.5)	672
		3	1.23 (9.2)	655
SW_C	Cedar	1	0.07 (2.3)	543
		2	0.20 (8.6)	561
		3	0.18 (3.3)	539
Mixed				
MW		1	0.26 (19.4)	616
		2	0.18 (12.1)	610
		3	0.15 (8.1)	603

Values in ( ) are cov in %. S = Sawdust, TL = Tradical Lime, HW_B = hardwood beech, HW_O = hardwood oak, SW_C = softwood cedar, SW_P = softwood pine, MW = mixed wood

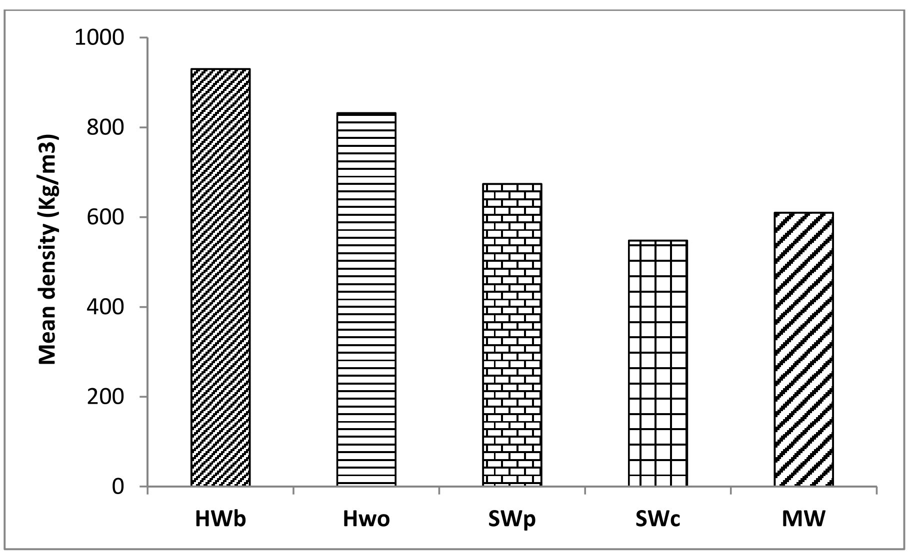


Fig. (2). Comparison of overall density among various wood specie.

Where, ρ = density of individual wood specie. This means that if the wood-crete has had the same compaction, the density of the wood-crete would have been equal to the calibrated density. Therefore, the compressive strength is calibrated to those that would have been the densities the same as the calibrated density (i.e. the same compaction). The calibrated results are summarised in (Table **6**).

It can be seen from the (Table **6**) that the wood-crete had been made with the same compaction (i.e. with the calibrated densities). The compressive strength was 26.4% higher for

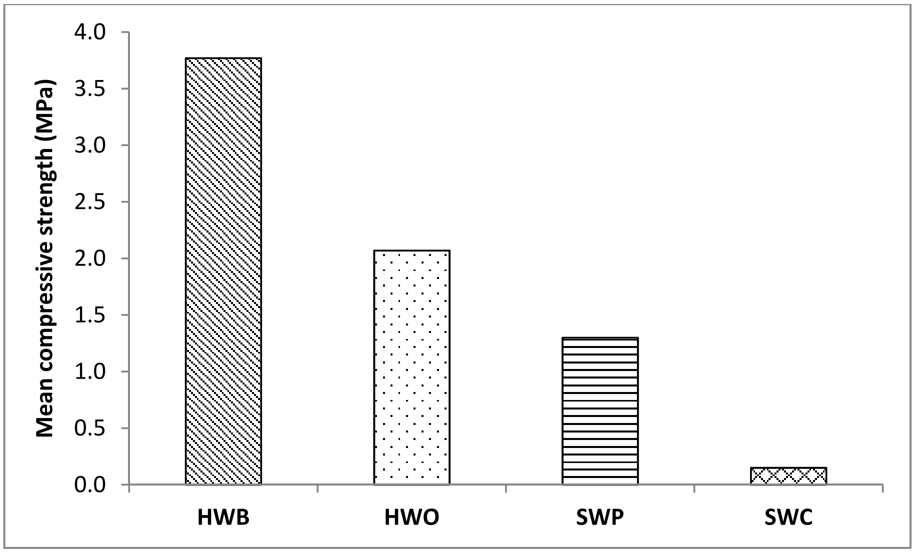


Fig. (3). Mean compressive strength vs wood species.

Table 6. Calibrated Density and Compressive Strength of Wood-Crete with Experimental Mixture Design

Samples		Particle size (mm)	Compressive Strength (mpa)	Calibrated Compressive Strength (mpa)	Density (kg/m3)	Calibrated Density (kg/m3)
Hardwood						
HW_B	Beech	1	3.93 (8.4)	4.14	934	1041
		2	3.90 (7.0)	4.12	930	1041
		3	3.44 (6.9)	3.64	929	1041
HW_O	Oak	1	2.19 (3.7)	2.41	859	1048
		2	2.07 (10.1)	2.32	821	1048
		3	1.95 (9.2)	2.19	816	1048
Softwood						
SW_P	Pine	1	1.37 (6.8)	1.59	696	966
		2	1.30 (4.5)	1.53	672	966
		3	1.23 (9.2)	1.46	655	966
SW_C	Cedar	1	0.07 (2.3)	0.09	543	973
		2	0.20 (8.6)	0.25	561	973
		3	0.18 (3.3)	0.23	539	973

Values in ( ) are cov in %. S = Sawdust, TL = Tradical Lime, HW_B = hardwood beech, HW_O = hardwood oak, SW_C = softwood cedar, SW_P = softwood pine

beech wood-crete compared to hardwood oak and 45.7% for softwood pine compared to softwood cedar. On average, the wood-crete made from hardwood sawdust records a much higher strength value (49.9%) than those made of softwood sawdust. This gives an indication that other factors such as higher lignin content in hardwood than softwood may affect the strength of wood-crete composites. Lignin has been reported by researchers to be a contributing factor to high performance concrete strength and improve compressive strength of cement paste. The combination of cellulose, hemicelluloses and extractives (sugar, fatty acid e.t.c) content is higher in softwood than hardwood which is another possible factor for the low compressive strength with wood-crete made from softwood. For example, research on the effect of sugar content on the property of composites showed that extracting sugar content from wood dust helps improve the bonding strength of composite materials which has an influence on compressive strength of wood-crete [16-18].

3.3. Correlation of Compressive Strength and Density

Average measured densities for wood-crete for hardwood, softwood and mixed wood respectively are used to plot their relationship with compressive strength (Fig. **4**). It is observed that the compressive strength increases with an increase in the density of wood-crete regardless of wood species. For the wood-crete made from hardwood oak, compressive strength increased from 1.95 to 2.19 MPa (5.8%) when the density of wood-crete increased from 816 to 859 kg/m3 (2.6%) and for the pine wood-crete from 1.23 to 1.37 MPa (5.4%) when density of pine wood-crete increased from 655 to 696 kg/m3 (3.0%). The results are in line with the normal expectation of increasing compressive strength with increasing density. As discovered in previous study [1], compaction in mould is one factor that may have resulted in a higher compressive strength. Apart from compaction factor another reason for the difference in strength of wood-crete from different types of hardwood is a variation in the property of raw materials themselves, such as a little difference in the compressive strength and actual density of various types of wood themselves. Density of hardwood oak is slightly higher than that of beech hardwood and the density of softwood cedar is higher than that of softwood pine.

The correlation of compressive strength with average density of wood-crete seems to be linear with a good degree of fit, R^2=0.94 (Fig. **4**). However, a further comprehensive design of density profile is required to achieve an accurate modelling result.

3.4. Correlation of Particle Size and Compressive Strength

It was noticed that the geometry of sawdust used had a significant impact on the strength of wood-crete. Of important point to note here as shown in (Fig. **5**) is that the blocks made with sawdust to tradical lime ratio of 1:1 both for 1mm, 2mm and 3mm particle sizes, were not subjected to compressive testing because the samples did not bond together after demoulding period of 24hours. This is because the strength properties of composites strongly depend on the stress transfer between particles and binder and strength reductions occur by either adding a disproportion of particles or increasing particle size. Wood-crete made with sawdust to tradical lime ratio of 2:1 with 1mm sieve size of sawdust achieved higher strength when compared to those made with 2mm and 3mm sieve size of sawdust of each type of wood used (Fig. **6**). In addition to the increase in strength associated with short fibres, it has also be discovered in a previous study by Migneault [19], that short fibres are the easiest to mix which enables fibres to be properly coated with matrix thus having effect on mechanical properties. It is also most interesting that the reduction of the compressive strength with the increase of the particle sizes is related to the density of wood species, i.e. the reductions in the compressive strength of hardwood-crete are more significant than those of softwood-crete. The reduction in compressive strength from 1mm to 3mm particle sizes is 5.8% for oak wood-crete, 6.6% for beech wood-crete, 3.4% for pine wood-crete and 27.9% for mixed wood. It was discovered that for cedar wood-crete, 2mm particle size achieved a higher compressive strength than 1mm particle wood-crete, while the strength is very similar between the wood-crete made with 2mm and 3mm particle.

The mean compressive strength of different particle size of hardwood, softwood and mixed wood are compared in (Fig. **6**), likewise the mean density against particle size in (Fig. **7**). It is evident that the compressive strength of wood-crete made with 1mm particle size hardwood had about 56% increase in strength properties when compared to same particle size of softwood. A 54% increase and 47% increase was also noticed in 2mm and 3mm particle sizes respectively. The effect of particle size on compression strength has been reported [20] where composite strength increased with decreasing particle size. Smaller particles have a higher total surface area for a given particle loading which indicates that strength increased with increasing surface area through a more efficient stress transfer mechanism [20]. Also, smaller particles can generally be well-bonded with binder compared to larger particles and such the applied stress can be effectively transferred to the particles from the binder and from the binder to particles, which improves the strength or load bearing capacity of the wood-crete under load [19].

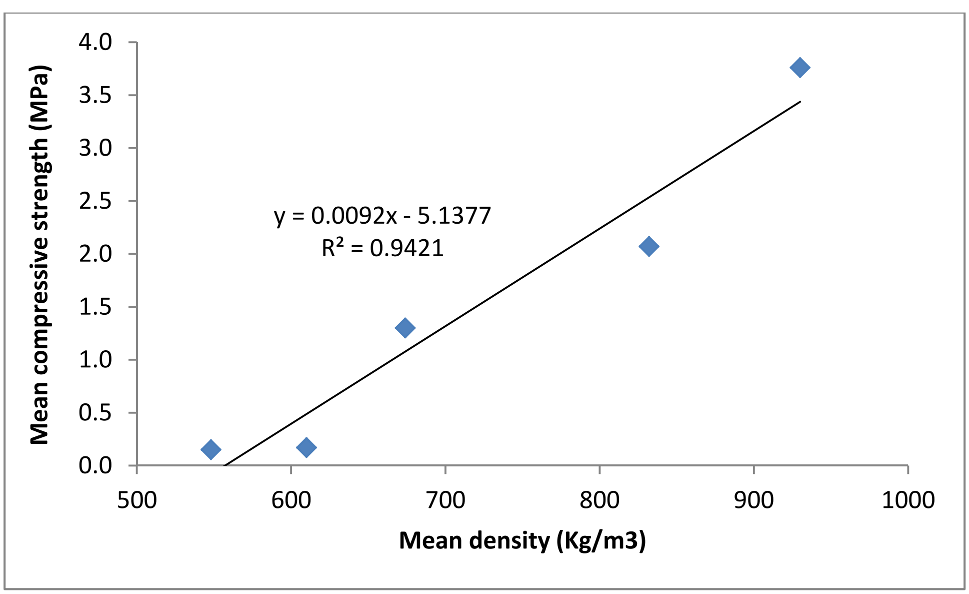
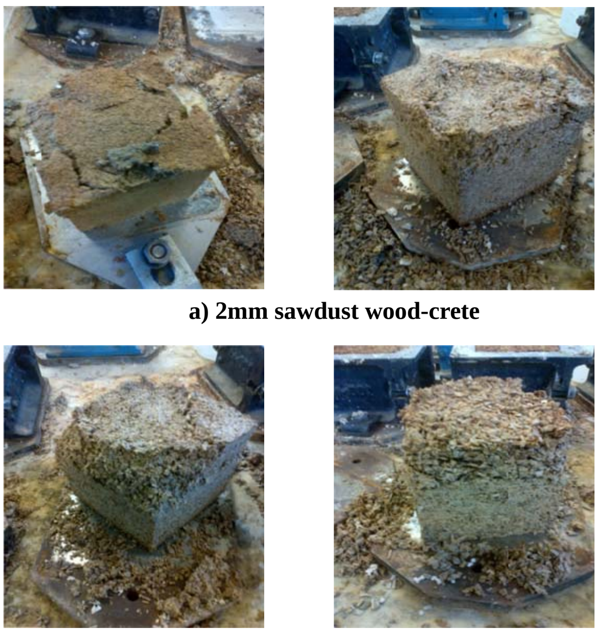


Fig. (4). Mean compressive strength against density.

Much higher reduction in the compressive strength of wood-crete made from the mixed wood from 1mm to 3mm in comparison with those made from hardwood and softwood emphasises an important consideration of the particle size distribution in manufacturing of wood-crete, because in practice it is very difficult to achieve a single wood species. This is because sawmills do not separate their wood waste during the sawing or milling process of wood. This implies that sieve sizes should be controlled during manufacturing of wood-crete in order to avoid low strength while ensuring that only wood-crete with desirable mechanical characteristics is formed.



a) 2mm sawdust wood-crete

b) 3mm sawdust wood-crete

Fig. (5). Poor bonding of wood-crete made with sawdust to tradical lime ratio 1:1 (demoulding after 24hours).

It is seen that the density of wood-crete made with particle size 1mm is about 0.8 and 1.5% higher than those of wood-crete made with particle size 2mm and 3mm respectively (Fig. **7**). The wood-crete made with the small particle size may be more compact while large particles not only retain the micro void within the sawdust, they may also create 'bridging' between particles.

3.5. Correlation of Wood Species with Thermal Conductivity

One of the main purposes for developing wood-crete as a building material is its thermal performance which is a key parameter in low carbon sustainable building construction. Thermal conductivity depends on the composition, density, pore structure, moisture content and temperature of a material [21, 22]. In wood, the main influencing factors are wood species, density, moisture content, direction of heat flow (anisotropy), inclination of grain and relation of volume or thickness to moisture content [23]. However, thermal conductivity is strongly influenced by density [21]. These have been reflected in the wood-crete developed in this study. It seems to be that wood-crete from softwood achieved a low thermal conductivity of 0.068 and 0.092 W/mK and wood-crete from hardwood achieved 0.114 – 0.123 W/mK (Table **7**). However, a scrutiny of the data in (Table **7**) showed that the trend of change in thermal conductivity of the wood-crete follows that of the density of the wood-crete, i.e. the ranking of thermal conductivity = the ranking of density = beech wood-crete > oak wood-crete > pine wood crete > cedar wood-crete. The wood species may have little effect on the difference in the thermal conductivity of wood-crete. This may be true by considering the thermal properties of wood reported by a previous worker [24], whose research on the thermal conductivity of five softwood and five hardwood showed that the average thermal conductivity for the former was 0.091 and for the latter 0.092 W/M.^{0}C. Thermal conductivity of wood-crete from cedar sawdust was about 15% lower than wood-crete from pine wood while thermal

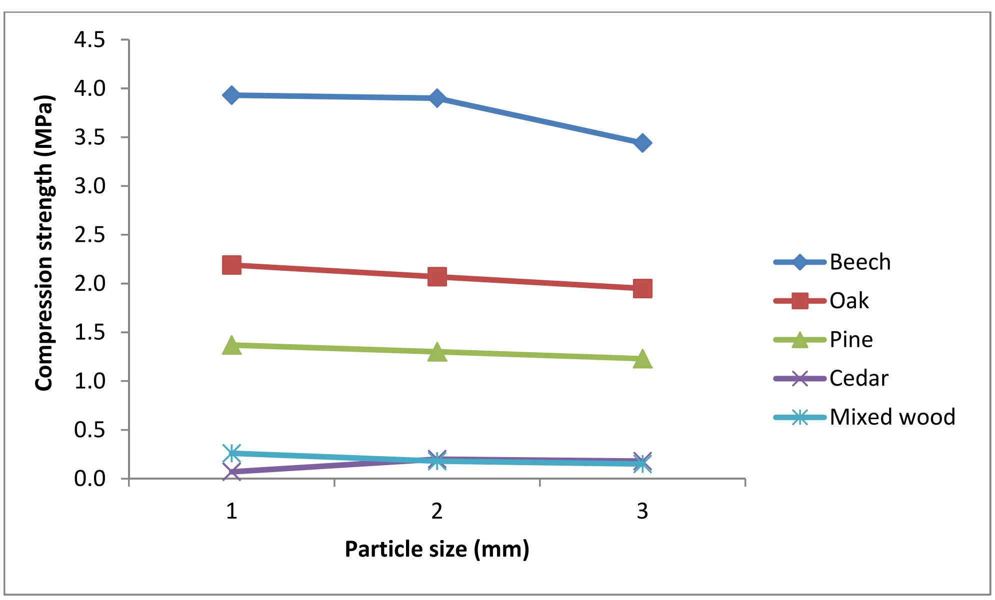


Fig. (6). Mean compressive strength against particle size.

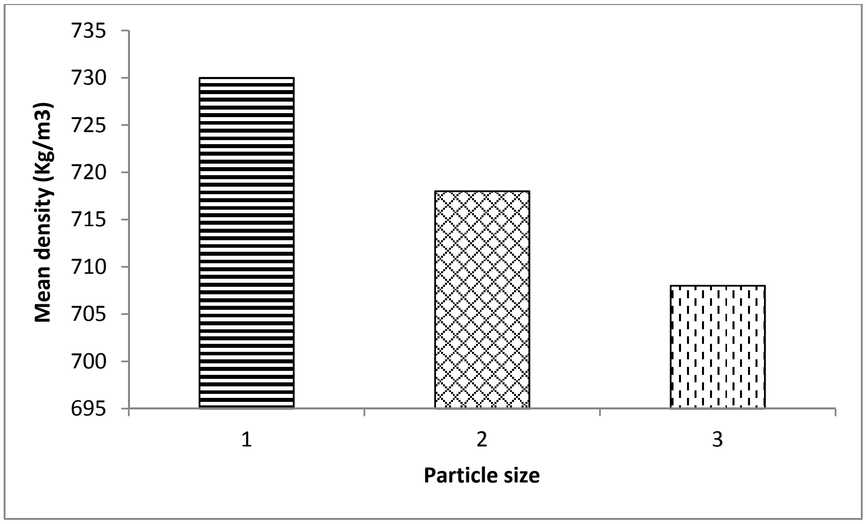


Fig. (7). Mean density against particle size for all wood species.

Table 7. Thermal Conductivity and Effusivity of Wood-Crete from Various Wood Species

Wood Species	Thermal Conductivity (W/M.^{0}C)	Thermal Effusivity (Ws½/m²K)	Compressive strength (MPa)	Density (kg/m3)
Pine	0.092	113.582	1.37	696
Cedar	0.068	106.156	0.07	543
Oak	0.114	115.277	2.19	859
Beech	0.123	116.014	3.39	934

conductivity of wood-crete from oak wood was about 3.8% lower than wood-crete from beech wood. These correspond to the fact that the density of cedar wood crete is about 22% lower than that of pine wood-crete, while the density of oak wood-crete is about 8% lower than beech wood-crete. The above result is also in agreement with results discovered in the previous study [1], where reduced density resulted in a low thermal conductivity.

4. CONCLUSION

The wood-crete made with hardwood, softwood and mixed wood species has been developed and the properties of the made wood-crete composites have been analysed. The compressive strength of wood-crete made from sawdust of softwood was similar to that of hempcrete and in some cases higher while compressive strength of wood-crete made from hardwood was higher than that developed in previous series of wood-crete [1]. This gives an indication that wood-crete made from specific types of wood can as well be used as in-fills in construction. However, the compressive strength of wood-crete were not comparable to those of normal concrete as the strength values were lower than those of concrete and some other building materials (Table **3**). Nevertheless, the compressive strengths were higher than those of hempcrete which is currently used in construction.

The properties of wood-crete were related to its composition and type of sawdust from different kinds of wood species. Conclusively,

Wood-crete made from hardwood resulted in higher strength compared to those made from softwood having a 53% difference in the compressive strength on average. Hardwood beech wood-crete recorded a 61% increase in compressive strength when compared to hardwood oak wood-crete; likewise softwood pine recorded a 79% increase in compressive strength when compared to softwood cedar wood-crete.

The constituents of wood (lignin, cellulose, hemicelluloses and extractives) all contributed to the strength properties of wood-crete composites.

To enable better bonding between sawdust and binder, a 1:2 of sawdust to binder ratio has been advisable.

Wood-crete made with smaller particle size of 1mm achieved better compressive strength than those made with 2mm and 3mm particle sizes respectively. A reduction in compressive strength with an increase of particle size was strongly related to wood species.

Wood-crete made from softwood has a lower thermal conductivity compared to wood-crete made from hardwood with a 19.4% reduction in thermal conductivity value.

Mixing wood species for wood-crete production did not result in an average performance equivalent to the average performance of wood species, indicating an adverse effect of the mixing, such as 'bridging' between particles.

CONFLICT OF INTEREST

The author(s) confirm that this article content has no conflicts of interest.

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