Structural suitability of 10-year old *Pinus caribaea* timber with a forest fire history in farm buildings

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Abstract: Forest fires in pine and eucalyptus plantations are common in Uganda especially in the dry periods. In an event of fire gutting a nearly mature plantation, tree farmers usually try to reduce losses by extracting and lumbering the residual trees for use in agricultural buildings. However, there is no empirical data to guide material selection based on strength and structural integrity of the timbers from burnt plantations. Therefore, this study investigated the effect of fires on selected physical and strength properties of timber extracted from a 10-year old stand of *Pinus caribaea* that had been burnt. Test specimens were prepared and tested for Modulus of elasticity (MOE), Modulus of Rupture (MOR) and compression parallel to the grain using a Testometric AX M500 – 25KN Universal Testing Machine in accordance with ASTM D 198 and BS 373. For comparison purposes, structural size specimens from the same age stands that were unaffected by fire were concurrently tested. The data were statistically analyzed using one-way Analysis of Variance test. The results indicated that burnt trees had significantly lower density, MOE and MOR than that of the unburnt trees. It is recommended that timber extracted from burnt trees should not be used for high strength structural purposes but could rather be used in low strength construction works such as shuttering and ceiling works.

Keywords: *Pinus caribaea*, forest fires, density, strength, MOE, MOR

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1 Introduction

In Uganda, commercial plantation forestry continues to grow at 2% annually (Nabatte and Nyombi, 2013). The increased investment in plantation forestry has been fueled by the growing infrastructure development over the last 15 years which has created a demand for construction timber. This is partly due to the fact that there is a deficit of wood supply from natural forests because of over exploitation and adverse degradation. Apparently only 5%-10% of the timber on market comes from natural forests in Uganda (Nabatte and Nyombi, 2013). With limited wood supply from natural forests coupled with the high cost of steel, aluminum and cast iron, the use of fast growing round wood or timber has been adopted as a substitute for light weight construction works such as wall cladding, roofing, ceiling, flooring and minimal load bridges (Zziwa et al., 2006; Zziwa et al., 2016). Globally forests are threatened by increasing incidences of forest fires with tropical

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countries such as Brazil, Australia and many in Sub-Saharan Africa suffering heavy forest cover losses due to wild fires (Archibald et al., 2012; Earth Policy Institute, 2009). Fire damages the forest ecosystem and disrupts environmental processes responsible for stable weather conditions and thus forest fires could heighten the adverse effects of global climate change (Ahmad et al., 2017). In Uganda, the commonly grown trees for commercial timber production include: Pinus sp (*P. Caribaea, P. Patula and P. Radiata*) and Eucalyptus sp. (Zziwa et al., 2009). Both species are prone to fires during the dry spells, but pine is more susceptible. The fire risk in pine stands could be attributed to the high resin content and the thick blanket of pine vines on the forest floor. In the event of fire the resin content and thick pine vines leads to quick spread and growth in intensity of the fires damaging large acreages of forest plantations (Küçük and Aktepe, 2017).

According to Bortoletto Junior and Moreschi (2003), forest fires could have different magnitudes and cause different damages depending on the wind velocity, age of the stand, stand spacing and duration of the fire. A fire intensity could be termed as a *crown* (i.e. if it destroys at least 50% of the crown) or superficial burning (i.e., if it only burns the lower regions of the tree and does not penetrate the inside of the stem) and whilst the fire effects could be categorized as first order or second order effects. The first order effect of a fire can be visualized as the occurrence of charred bark and charred patches of the stems (Tremblay et al., 2018). This can be later followed by cambium and leaf or needle necrosis while complete plant mortality will usually manifest within a few months to three years after the fire. Second order fire effects are basically related to the invisible internal physiological changes that affect the proper growth of the surviving trees, such as increased sensitivity to adverse environmental conditions, insect and disease attack (Butler and Dickinson, 2010).

It is important to note that not all trees die off after a fire; some trees will always be surviving (Odhiambo et al., 2014). The survival of trees after an occurrence of a forest fire depends on several factors include: age, species, bark thickness, moisture content, chemical composition, density, root type, depth and intensity, duration and type of fire. According to Odhiambo et al. (2014), the ability of individual plant cells to withstand exposure to high temperatures does not vary significantly between plant species or between plant tissues within a plant. However, the lethal temperature for mesophytic plants generally ranges from 50°C to 55°C while a temperature above 60°C is lethal for the cambium (Odhiambo et al., 2014). For trees with thick and tough bark such as pinus sp, their thick bark is sufficient to insulate the cambium from lethal temperatures especially during a superficial fire occurrence. Several studies have suggested a linear correlation between bole diameter and bark thickness. Due to this linear relationship, smaller diameter trees may be survived even low intensity fires (Rust, 2015). Short exposure intervals to medium temperatures (<200°C), may only cause superficial deterioration with lower mechanical damage but short term exposure to temperatures above 200°C will lower strength (Sinha, 2013).

The impact of fire on the mechanical properties of wood generally occurs through altering the chemistry of the three wood structural components i.e., cellulose, hemicellulose and lignin (Bortoletto Júnior and Moreschi, 2003; Forest Products Laboratory, 2010). Considering the anatomical structure of wood, cellulose and hemicelluloses form the wood fibres (micro fibrils) while lignin forms the outer cementing material to micro fibrils. The tensile strength and stiffness of wood comes mainly from cellulose strings within the fibrils while lignin contributes to compression strength and additional stiffness (Desch and Dinwoodie, 1996). When wood is exposed to heat (i.e. >200°C), the cellulose fibres disintegrate while at >300°C lignin softens up thus the affected wood loses its tensile and compressive strength (Meincken and Berger, 2014). Exposure to heat above evaporative points (>100°C) also affects the wood extractives in the cell wall because their solubility in water is activated and then they migrate out of the cell wall leading to severe rapture in cell wall due to the high vapor pressure. Consequently, the loss of extractives and rapture of the cell walls results into a reduction of density and compounds the reduction in elasticity properties (modulus of elasticity (MOE) and modulus of rapture (MOR)), and notably compression parallel-to-grain (Brito et al., 2008).

A study by Sseremba et al. (2011) revealed that pine wood was the most sought after timber for roofing, interior wall cladding and furniture construction in Uganda. With the higher demand than supply, issues of quality have become a challenge especially regarding timbers coming from privately owned plantations. Since various structural applications require materials with specific strength qualities, application of materials with unknown strength quality for the construction of structures may lead to unpredictable life spans of the structures. Quality is further compromised by harvesting juvenile wood from burnt plantations. Although some studies on the impact of fires on the physical and mechanical properties of timber quality have been done elsewhere, there are no studies done yet on Uganda about the grown plantation species. As a result, data from literature may not be directly applicable in Uganda because of the different fire dynamics (Zziwa et. al. 2010). For instance, Turinawe et al. (2014) compared different varieties of Ugandan grown eucalyptus to those originating from South Africa including clones and the results showed a significant difference in physical and mechanical properties which were largely attributed to differences in silvicultural practices and soil conditions. Therefore, taking into account that variations in wood properties occurred due to other reasons, this study aimed at bench marking "Ugandan case" by evaluating the impact of fire on timber strength quality. The results from this study will contribute to the market information for material selection from woodlots that are prone to forest fires.

2 Materials and methods

2.1 Sampling

Sample trees were obtained from a 10-year old stand of burned and unburned trees at Corewoods Company Limited pine plantation, which is located in Hoima District, Western Uganda (1^{o}32'N and 31°12'E). The plantation is 40 ha with an average tree spacing of 6 m×6 m. The portion of the plantation from which burned trees were sampled was 28 ha. Within the burnt compartment, five (5) random plots of 50 m × 30 m were set out from which 5 trees with visible evidence of first order burning (>50% charred bark) were selected. A total of 25 trees were selected for the extraction of the burned samples here after referred to fully burnt wood (FBW). The same procedure was followed to sample 25 trees within the unburned compartment to extract samples hereafter referred to as non-burnt wood NBW.

2.2 Sample preparation

The harvested boles (on average 9 m height, 25 cm butt diameter and 10 cm top diameter) were cut into shorter sections (≈ 2.5 m) representing the top, middle and butt sections. The logs were sawn using through and through method. Sample timbers were marked to identify their origin and air dried to reduce the moisture content to 12%±3% (Glass et al., 2010). Moisture content (MC) was monitored using a moisture meter. The specimens were prepared according to ASTM D198 (2003). In addition, density as an indicator of strength was also determined. Structural size specimens for flexural strength determination were planed to 50 mm width, 50 mm depth and 1000 mm length. All specimens were labeled as FBW and NBW to represent timber that was burned or unburned respectively.

2.3 Determination of properties

The target properties were density, MOE, MOR and compression parallel to the grain.

2.3.1 Determination of density

Thirty five (35) specimens measuring 20 mm × 20 mm × 20 mm were used for the density determination. The basic density tests were done in accordance with British Standard BS 373 (1957). This standard specifies that density of wood can be determined from the ratio of its oven dry weight to its green weight. The green volume was obtained by the water displacement method based on Archimedes principle. A beaker of distilled water was placed on a balance and reset to zero reading. Using a needle tied to a string each specimen was gradually immersed under water and the green weight (G_w) equal to the water displaced was recorded. The test specimens were then oven-dried at 105°C ± 1°C until constant weight (D_w) in grams. The basic density in kgm^{-3} was calculated from Equation 1:

$$\rho = \frac{D_w}{G_w} \times 1000 \tag{1}$$

Where: ρ is the density in kgm^{-3}, D_w is the oven-dry weight in grams and G_w is the green weight in grams.

2.3.2 Determination of MOE and MOR

Timber flexural strength evaluation was done on a Testometric AX M500 – 25KN universal testing machine connected to a computer to plot the stress/strain curves. American Standard for Testing Materials - ASTM D 198 (2003) standard test methods of static tests of timber in structural sizes was adopted in the determination of MOR and MOE. In principle, this involved determination of maximum load required to cause rupture of test structural specimens and estimation of stress at this load. Specimens were subjected to uniform loading using a Universal Testing Machine, Olsen Tinius (Figure 1). The load was applied to the radial surfaces of test pieces midway between the supports using four-point loading. The loading speed was 6 mm per minute to ensure rupture of structural specimens in 1.5 ± 0.5 minutes from the start of loading.

Figure 1 The universal testing machine

The MOR of the test specimens was determined using Equation 2:

$$MOR = \frac{1.5P_{max}L}{bh^2} \tag{2}$$

Where: MOR is the modulus rupture in N mm^{-2}, P_{max} is the breaking load in Newtons; L is the distance from supports in mm; b is the breadth of the test piece in mm; and h is the depth of the specimen in mm.

The MOE was calculated according to Bowyer (2003) using Equation 3:

$$MOE = \frac{PL^3}{48ID} \tag{3}$$

Where: MOE is the modulus of elasticity in N mm^{-2}, P is concentrated centre load (Newtons); D is deflection at mid span (mm) due to P; L is the span (mm) and I is moment of inertia in mm^4 as given by Equation 4:

$$I = \frac{bh^3}{12} \tag{4}$$

Where: b is the breadth of the test piece in mm and h is the depth of the specimen in mm.

2.3.3 Determination of compression parallel to grain

The ultimate compression stress parallel to the grain was determined by testing small clear specimens measuring 60 mm × 20 mm × 20 mm in compression parallel to grain until failure occurs, at a rate of 0.6 mm per minute (Dinwoodie, 1981) using a Testometric AX M500 – 25KN Universal Testing Machine. The specimen was loaded to failure and the maximum load P_{max} was recorded. The ultimate stress in compression parallel to grain σ_c of each test specimen was calculated in N mm^{-2} using Equation 5;

$$\sigma_c = \frac{P_{max}}{bd} \tag{5}$$

The maximum load (P_{max}) was recorded and the maximum compressive stress parallel to the grain in N, (σ_c) in N mm^{-2} was calculated using Equation 4 where b = d =20 mm (cross sectional dimensions of test piece).

2.4 Data analysis

Descriptive statistical procedures were used to obtain means and standard deviations for all test properties using Sigma plot software (version 14, Systat. Inc. USA). The data failed to meet the conditions of Normality Test (Shapiro-Wilk) at ($P < 0.05$); therefore non-normality Kruskal-Wallis One Way ANOVA coupled with Tukey Posthoc analysis was used to compare the mean parameters for the two groups. In order to accommodate the influence of natural variations within the trees and any other sources of variation during the experiment, order statics (percentiles) were used to generate a tolerance interval within which 90% of the measured properties of a given test specimen are likely to fall at 95% confidence level.

3 Results and discussion

3.1 Mean density, MOE, MOR and compression strength

The mean values of the physical and strength properties for both the burned and unburned wood are summarized in Table 1.

Table 1 Descriptive statistics for density and mechanical properties

Property	Variable	Mean ($N\ mm^{-2}$)	Std. Dev.	Std. Error	25%	75%
Density	Burned wood	307.31	14.40	2.63	299.25	323.45
	Unburned wood	341.70	16.50	3.02	329.35	350.43
MOE	Burned wood	8233.40	2327.10	424.88	6335.13	9868.90
	Unburned wood	10176.50	3104.50	566.80	7462.93	12817.50
MOR	Burned wood	80.51	23.74	4.34	59.01	101.77
	Unburned wood	102.3	41.48	7.57	65.57	132.73
Compression Parallel to grain	Burned wood	48.10	3.93	0.72	45.64	50.92
	Unburned wood	57.45	9.83	1.80	51.63	67.33

Figures 2 to 5 show the mean physical and mean strength properties of burned and unburned wood.

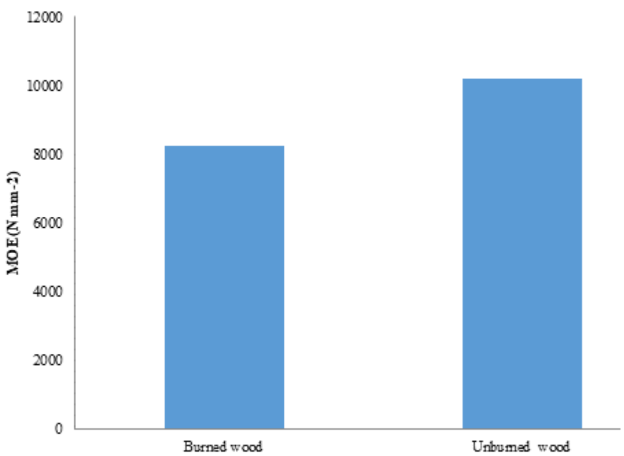

Figure 2 Mean MOE of burned and unburned wood

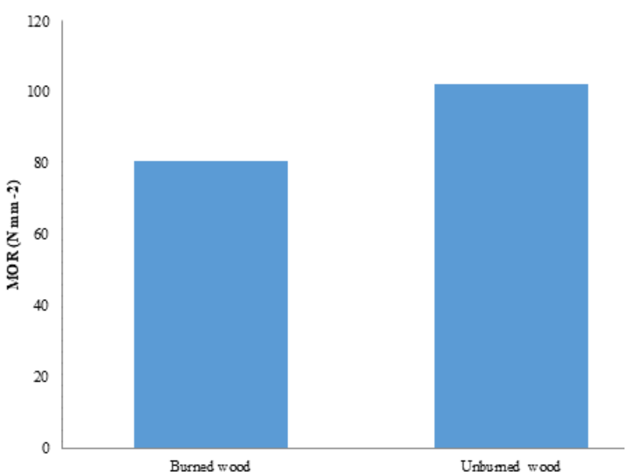

Figure 3 Mean MOR of burned and unburned wood

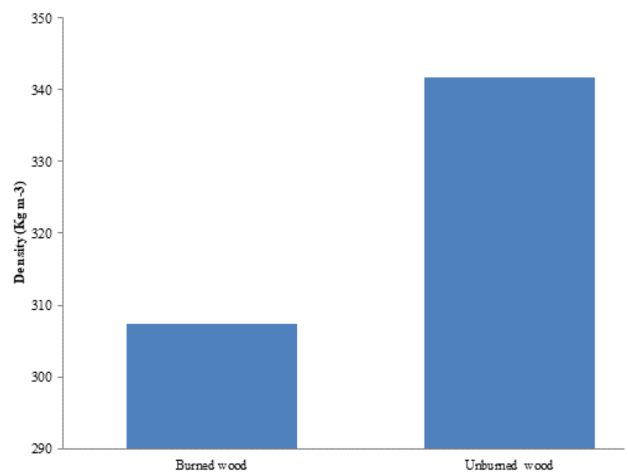

Figure 4 Mean density of burned and unburned wood

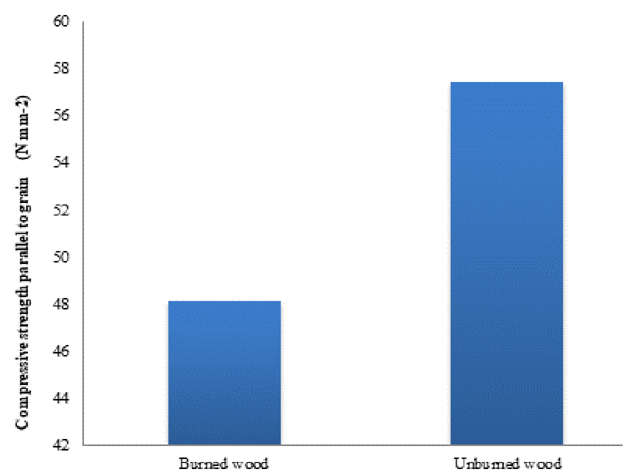

Figure 5 Mean compressive strength parallel to grain of burned and unburned wood

3.2 Basic density

The basic density was measured based on a pooled sample of 40 specimens. In general, the wood density of all the tested specimens was below the normal range for pines wood which is 360 – 680 kg m^{-3} (Schneider et al., 1991) and were in particular lower than those reported in previous Ugandan studies on *P. caribaea* timbers by Zziwa et al. (2009) and Ishengoma et al. (2007) which ranged from 424 - 444 kg m^{-3}. Statistical analysis Analysis of Variance (ANOVA) proved significant differences in the density comparing burned and unburned wood (Table 2). There was a 10% loss in density in the burned wood in comparison to the unburned samples.

Table 2 Kruskal-Wallis One Way ANOVA for density for burned and unburned wood samples

Group	ANOVA Variables			Tukey Posthoc Test		
	Median	H-value	P (H-statistic)	Difference of Ranks	q value	P value (q statistic)
Burned wood	307.291	32.399	<0.001	770.0	8.05	<0.05
Unburned wood	341.697					

From the Table 2, the differences in the median values among the treatment groups are greater than that expected by chance. There is a statistically significant difference (P = <0.001) in the mean density values of burned and unburned wood, which indicating that the strength quality of *Pinus caribaea* timber is adversely affected by the fire accident.

3.3 MOR and MOE

Similar to basic density, the MOR and MOE of the burned wood was lower than that of the unburned (Figures 2 to 5) wood clearly showing the potential damage by fire. In particular, the MOR was reduced by 21.3% and the MOE to 19% in the burned specimens as compared to the unburned wood (Table 1). Statistical analysis (Table 3) showed that there was significant difference in MOE between the burned and unburned wood samples. However, the mean MOR values were not significantly different between the burned and unburned wood (Table 4).

Based on the H-static and q-value in Table 3, the difference in the median values among the treatment groups is greater than that expected by chance, hence, there is a statistically significant difference (P < 0.013) in the mean density values of burned and unburned wood.

Table 3 Kruskal-Wallis One Way ANOVA on MOE for burned and unburned wood samples

Group	ANOVA variables			Tukey Posthoc Test		
	Median	H-value	P (H-statistic)	Difference of Ranks	q value	P value (q statistic)
Burned wood	7892.63	6.169	0.013	336.0	3.51	<0.05
Unburned wood	9255.48					

Table 4 Kruskal-Wallis One Way ANOVA on MOR for burned and unburned wood samples

Group	ANOVA Variables			Tukey Posthoc Test		
	Median	H-value	P (H-statistic)	Difference of Ranks	q value	P value (q statistic)
Burned	81.585	3.307	0.069	-	-	-
Unburned	94.815					

From Table 4 based on the H-statistic and q-value, the differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P > 0.05).

3.4 Compression strength parallel to the grain

The mean compression strength was 57.45 and 48.10 N mm^{-2} for the unburned and burned wood respectively. The compressive strength in burned wood was reduced by 16.3% compared to the unburned wood. Statistical analysis based ANOVA revealed the significant differences between the two groups as reported in Table 5. Based on the H-static and q-value in table 4, the difference in the median values among the treatment groups is greater than that expected by chance hence there is a statistically significant difference (P < 0.013) in the mean density values of burned and unburned wood.

ANOVA showed that there was a significant difference in density, MOE and compression parallel to the grain (Tables 2, 3 & 5) of the wood cut from the burned and unburned trees. This was expected because of the fire effect which could have caused deterioration of structural polymer compounds and consequently loss in fiber material (Brito et al., 2008; Meincken and Berger, 2014).

Table 5 Kruskal-Wallis One Way ANOVA for Compression Strength parallel to the grain for burned and unburned wood samples

Group	ANOVA variables			Tukey Posthoc Test		
	Median	H-value	P (H-statistic)	Difference of ranks	q value	P value (q statistic)
Burned	47.575	18.01	<0.001	574.0	6.00	<0.05
Unburned	54.969					

The lower density in unburned wood could be attributed to the age of the wood and perhaps the growing conditions as the references by Zziwa et al. (2010) and Ishengoma et al. (2004), the tested pine wood was aged above 20 years. This is line with earlier studies that have stressed the dependence of wood density and strength properties on tree age (Horáček et al., 2017). The density of 10 year old trees sampled in the study as would be expected is less than that of 20 year old trees because juvenile wood is usually characterized by shorter tracheid length and thinner cell walls than mature wood (Deng et al., 2014), which result in low density. Nonetheless, the applications to which round wood are usually put to do not necessitate extra-strong wood. Hence 10–year old timber can provide adequate structural integrity in those applications. This finding indicates that efficient wood utilization can be achieved through timber specification based on species and age and matching these to various end-uses.

The significant difference in compression parallel to the grain is attributed to degradation of hemicellulose during attack by forest fires. This statement is in agreement with Sinha et al. (2011) who studied thermal degradation of strength properties of wood after exposure to elevated temperatures and discovered that as hemicellulose degrades, acetic acid is formed, which reduces the degree of polymerization of glucose, by breaking glycoside bonds. This leads to reduced mechanical strength in wood. According to Navickas et al. (2013) the compressive strength increases after heat exposure because of the increase of cross linking of the lignin polymer network and increase of the crystalline cellulose. These are opposite results to the findings in this study probably because of the research methods used.

Timber obtained from trees that were exposed to fire was also found to have significantly lower modulus MOE and MOR compared to unburned timber. The loss in elasticity and breaking strength in burned wood could be attributed to mass loss due to the degradation in hemicellulose (Esteves and Pereira, 2009). According to Meincken et al. (2010) the decrease in MOR is attributed to the degradation of lignin. This result is corroborated by the decrease in density for the burned wood (Table 2). From Table 2, the average wood density of timber obtained from trees that were exposed to fire (burnt wood) was lower than that of the unburned timber.

Zziwa et al. (2009) carried out an extensive study of Ugandan timbers (both soft wood and hardwood) for about 22 different species. The major aim of the study was to characterize the mechanical strength and use it as a basis for structural grading of timber according to the allowable stress bearable when used in construction. From the results, four strength classes were derived as shown in Table 6.

Table 6 Timber strength classes based on strength values (Zziwa et al., 2009)

Strength Class	Mean Allowable MOR ($N\ mm^{-2}$)	5^{th} Percentile MOR ($N\ mm^{-2}$)	Mean MOE ($N\ mm^{-2}$)
SG4	4	10.60	5710
SG8	8	21.20	8148
SG12	12	31.80	9710
SG16	16	42.40	11898

From Table 6, for each strength class (e.g. SG4. 8-16), the number refers to the allowable bending stress to resist failure during use in construction. For instance, G8 refers to a timber with an allowable bending stress of 8 Mpa.

Zziwa et al. (2009) recommended that timbers in strength class SG8 and SG12 were appropriate for the construction purposes where stiffness (MOE) was a controlling factor and where high strength requirements (MOR) were not so critical while SG16 was recommend for structural purposes where strength was a much needed requirement such as in beams and heavy load roofing.

Another study by Kityo and Plumptre (1997) on characterization of marketable soft woods and hardwoods of Uganda classified the timbers based on end use purpose based on density, MOR and MOE values as listed in Table 7.

The British Standard timber strength grading system (BS 5268 part 2) specifies strength characterization of timber as ranging from C14 - C4O for coniferous (soft wood) pine inclusive (Table 8). From Table 8, the numbers refer to the characteristic bending stresses i.e. the ultimate strengths of the woods in N mm^{-2} before safety factors and margins for loading conditions are included. The class range from C14 to C22 is for low-to-light construction purposes. The class range C24-C30 is recommended for medium load construction whilst C35-C40 is recommended for medium-to-heavy load construction.

Table 7 Classification of timber basing on Density, MOE and MOR (Kityo and Plumptre, 1997)

Classification	MOR (N mm^{-2})	MOE (N mm^{-2})	Basic density (kg m^{-3})
Heavy construction	≥133	≥14700	≥720
Medium construction	89-132	9900-14700	480-720
Light construction	39-88	6860-9800	400-480
Low loading Construction	>39	<6860	<400

Table 8 The British standard timber strength classification system (BS 5268:2)

Strength Class	Bending Parallel to grain (N mm^{-2})	Tension parallel to grain (N mm^{-2})	Compression parallel to grain (N mm^{-2})	Shear parallel to grain (N mm^{-2})	MOE (N mm^{-2})	Density (kg m^{-3})
C14	4.1	2.5	5.2	2.1	6800	350
C16	5.3	3.2	6.8	2.2	8800	370
C18	5.8	3.5	7.1	2.2	9100	380
C22	6.8	4.1	7.5	2.3	9700	410
C24	7.5	4.5	7.9	2.4	10800	420
C27	9.5	6	8.2	2.5	11500	450
C30	11	6.6	8.6	2.7	12300	460
C35	12	7.2	8.7	2.9	13400	480
C40	13	7.8	8.7	3	14500	500

Note: Source: British Royal Institute of Standards (www.roymech.co.uk/usefultables/Timber_design.html)

Based on the first on the three strength classifications (i.e., by Kityo and Plumptre, 1997; Zziwa et al., 2009; and BS 5268 Standard, 1996) the results of this current study come short of what is specified for heavy and medium weight construction purposes. However, they are within range for light weight construction uses. Surprisingly, even though some significant difference in measured parameters existed between the burned and unburned wood tested from our study, the three grading systems from literature qualifies them for similar strength classification and enduse purposes.

4 Conclusions

Pinus caribaea timber from trees exposed to fire has significantly lower density, flexural and compression strength parallel to the grain than timber from trees that were not exposed to fire. Therefore, timber from pine trees of up to 10 years of age with a fire history should not be used for structural applications, which requiring high strength requirements in buildings but could be used for lighter construction purposes such as scaffoldings and ceiling paneling. The study has also indicated that the effect of tree age on physical and mechanical properties of pine makes harvesting age a critical factor in ascertaining suitability of pine for structural application. Further research on the potential effect of fire on natural durability of wood and machining properties should be done to widen the scope of understanding of the effects of fire on the structural strength quality of timbers on the market. In addition, further research should be carried out to ascertain how density and strength of *Pinus caribaea* trees at full maturity is affected by fire exposure.

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