Physical, Morphological, and Mechanical Properties of Major Timbers for Sustainable Infrastructure: A Review

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***Abstract*—Timber is a preferred alternative sustainable and green construction materials to concrete for construction purposes. Specifically, timbers are renewable anisotropic materials with a long application history in human society. They are of numerous species, varieties and ultimately, characterization. These differences demarcate the extent of its usage and application, especially in structural and construction purposes. This paper presents an extensive review of the historical significance of timber as a sustainable construction materials including the physical properties – density and specific gravity, moisture content and shrinkage, and colour and texture. Also considered in this piece are the morphological characteristics, mechanical properties and the critical factors that influence timber properties. The review closes with the practical applications of major timbers, sustainability and environmental impacts and future research directions.**

***Keywords*—Timber, tree species, mechanical properties, physical properties, morphological characteristics, growth rings, grain orientation, sustainable timber infrastructure**

I. INTRODUCTION

Jumaat et al. [1] presents new strategies for timber engineering in Malaysia through engineering education and research. Additionally, the eco-friendly attributes of timber including non-toxicity, renewability, sustainability, low carbon footprints, and low energy demand further underscore the historical significance and continued relevance of timber in modern construction [2–5]. The mechanical properties of timber, including its anisotropic nature and variability, have posed challenges in its structural application, leading to the need for stochastic approaches to accurately assess the reliability of timber structures. This historical context is crucial for understanding the physical, morphological, and mechanical properties of major timbers, providing a foundation for the comprehensive study of timber in various applications [6–17].

The study of timber properties encompasses a wide range of physical, morphological, and mechanical characteristics that are essential for understanding the behaviour and potential applications of different timber species. A couple of studies has been reported on the classification of common Nigerian timber species based on their strengths - in pure tension, shear and flexure – to provide valuable insights into their load-bearing capabilities. Such classification is essential for ensuring the appropriate selection of timber for various structural applications, contributing to the safe and efficient use of timber in construction and engineering projects. Adekunle et al. [18] and Oyediran et al. [19] conducted experimental works to determine the physical and mechanical properties of three timber species in Abeokuta in Ogun State and five different species in Iwo in Osun State respectively in Nigeria based on BS EN 13183 [20] and BS EN 408 [21]. The physical properties investigated included density, moisture content, colour and texture. The mechanical properties were experimentally conducted in the laboratory in accordance with ASTM D143[22] and ASTM D198[23] to evaluate the bending strength, compressive strength, shear strength, tensile strength, modulus of elasticity, and modulus of rupture. Their findings showed that all the investigated timber species except Terminalia superba (Afara) have mechanical properties of higher values than those ascribed to classes of strength D30 to class D70 in the British Code of Practice. This therefore showed that all except Terminalia superba (Afara) are recommended for structural applications.

Other studies have reported the importance of understanding the fracture behaviour of wood, stressing that despite timber's widespread applications in construction, research on its fracture mechanics is comparatively very limited [24, 25]. The strengths of timbers have been hampered by defects such as checks and knots. Hence, extensive studies are essential to apply quantitative fracture mechanics techniques to assess the strength-reduction factors of flawed timber. This underscores the complexity of evaluating timber properties and the need for comprehensive studies to understand the behaviour of wood as a structural material.

II. PHYSICAL PROPERTIES OF TIMBER

The physical properties of timber have direct influence on the behaviour and potential applications. Density (or specific gravity), moisture content and shrinkage, as well as colour and texture are fundamental characteristics that characterize the physical nature of different timbers [10, 26–28]. Extensive studies have been conducted on the effect of finishing materials on the physical properties of timber, thereby revealing significant differences in basic wood density, wood shrinkage, and water absorption ability among different tree portions and treatments [10, 29–33]. In addition, the tensile strength of timber is a critical mechanical property of axially loaded tension and flexural members that varies with moisture content and grain orientation, with cross grain reducing the tensile strength of wood. Experimental and numerical studies have shown that tensile strength increases with decreasing moisture content below the fibre saturation point and is influenced by the orientation of the grain [34].

A. *Density and specific timber*

Density and specific gravity are crucial quantitative measures that define the physical properties of timber [10, 35, 36]. Density is a key indicator of timber strength and suitability for various applications. The moisture content of wood is an essential consideration when determining its density, with basic density obtained using green volume and oven dry weight of sample discs. The volume of each sample is determined using the water displacement method, and the basic density is subsequently calculated [8, 10, 35–40]. Additionally, shrinkages are evaluated from samples at the green stage and after drying up to a constant weight, with three-dimensional measurements made for radial, tangential, and longitudinal lengths [41, 42].

Specific gravity, on the other hand, is another important measure that helps in assessing the suitability of timber for specific uses. It is a measure of the ratio of the density of wood to the density of water, which provides insights into the relative heaviness of a timber species. The physical and mechanical properties of selected timber species are often evaluated in accordance with specific standards [20–23] to provide a comprehensive understanding of its characteristics. These measures provide valuable insights into the quality and performance of timber, thereby guiding an informed decision-making process for various construction, fabrication and manufacturing purposes.

B. *Moisture content and shrinkage*

Moisture content and shrinkage are critical properties of timber that significantly impact its dimensional stability and mechanical behaviour [8, 43–45]. Wood is an anisotropic material with distinct differences in tangential and radial shrinkages [41, 42, 46]. The shrinkage ratio varies with moisture content (MC). As MC decreases below 25%, the shrinkage ratio exhibits a linear decline in both tangential and radial directions, with the final shrinkage ratio at about 5.5% in the tangential direction and 3.5% in the radial direction at the end of drying [41]. Slight shrinkage associated with the fiber saturation point (FSP) occurs below 35% MC. Below the FSP, the bound water is lost from the cell wall leading to dimensional changes in wood.

Furthermore, studies have shown that larger cross-sectional dimensions of lumber are associated with more severe surface cracking during drying, and the moisture content gradient between the heartwood and sapwood regions influences the shrinkage behaviour [5, 25]. Laboratory experimental testing and numerical or statistical simulation prediction are pivotal to understanding moisture content gradients and shrinkage behaviour, with two-dimensional models being developed to predict moisture content distribution during the drying process of wood [9]. Understanding these phenomena is crucial for optimizing timber drying processes and designing timber structures with enhanced dimensional stability.

C. *Colour and texture*

Colour and texture are crucial aesthetic and tactile aspects of timber that significantly influence its utilization in various industries such as furniture, interior design, and construction. The color of timber is influenced by various factors including species, age, and environmental conditions during growth; while texture is determined by the arrangement of wood fibers [13, 47–48]. Fujisaki et al. [49] evaluated the material properties of wood based on visual, auditory, and tactile assessments and found that the affective properties are similar, even when carried out separately. Multiple regression analysis also revealed strong associations between perceptual and affective properties for vision, audition, and touch.

Wan et al. [50] underscored the significance of colour and patterns in creating meaning for the user or onlooker, which can be captured through different associations or descriptive terms. This highlights the importance of understanding the visual appeal of timber in the marketing and communication of wood products. Additionally, the importance of considering aesthetic properties alongside physical and mechanical properties when selecting timber for specific structural end-uses cannot be over emphasized because the correct use of timber can enhance the durability of the final product [2, 15, 31]. These insights emphasize the need for a comprehensive understanding of the colour and texture of major timbers, as they play a vital role in both the commercial and practical aspects of timber utilization.

III. MORPHOLOGICAL CHARACTERISTICS

The morphology of timber play a crucial role in determining its properties and behaviour [14, 51–53]. An exploration of the anatomical structure reveals important details such as growth rings and grain orientation. The microstructure-stiffness relationships of various hardwood species have been studied to shed light on the distributions of tracheid cross-sectional dimensions in different parts of Norway spruce stems [54, 55]. Furthermore, the hierarchical modeling of microstructural effects on mechanical properties has been investigated, emphasizing the influence of wood quality and the juvenile-mature wood transition based on tracheid length in species like white spruce [47, 56]. Understanding these morphological characteristics is essential for characterizing the internal composition and organization of timbers, which significantly influence their mechanical properties.

Moreover, the tensile strength of wood has been found to increase with decreasing moisture content below the fiber saturation point, with the highest values obtained in straight-grained specimens with thick-walled fibers [11, 34, 43]. However, cross grain has been found to reduce the tensile strength of wood, highlighting the significance of grain orientation in understanding the mechanical behaviour of timber [5, 57–60]. These findings establish the intricate relationship between the morphology and mechanical properties of major timbers.

A. Anatomical Structure

The anatomical structure of timber plays a crucial role in determining its physical and mechanical properties [61, 62]. The significance of understanding the relationships between microstructure and stiffness of different wood species highlight the importance of vessel arrangement and cellular composition. Several studies have reported the microscopic structure of wood and established a correlation between anatomical properties and the potential utility of a wood species for structural purposes [27, 28, 61–64]. These findings underscore the essentiality of detailed anatomical studies in assessing the suitability of timber for various applications, such as construction and furniture production. Understanding the cellular composition and vessel arrangement is crucial for comprehending the unique characteristics of different wood species, ultimately influencing their utilization in the timber market [56, 63, 65].

B. Growth rings and grain orientation

Growth rings and grain orientation are crucial factors that influence the physical and mechanical properties of timber [5, 64–67]. The growth rings, also known as annual rings, are formed by the contrast between early wood and latewood, which impacts the density and strength of the wood [68]. The orientation of the wood grain, whether it is straight, interlocked, or spiral, significantly affects the timber's stability, workability, and resistance to warping and splitting.

Additionally, the longitudinal shrinkage of timber, influenced by growth stresses and compression wood, can lead to material distortion and a greater tendency to bow, impacting the utilization and mechanical properties of the wood [9, 45, 58, 67, 68]. The intra-ring compression strength is a pivotal to understand the mechanical properties of different wood types, as it reflects the load-carrying capacity of the wood parallel to the grain. Hence, understanding the growth rings and grain orientation of major timbers is essential for optimizing their utilization in various applications and industries [8, 58].

IV. Mechanical Properties of Timber

Mechanical properties of timber, such as strength and stiffness, play a crucial role in determining its performance in various applications [7, 11, 16–18, 69]. Adekunle et al. [18] found that the characteristic bending strength and modulus of elasticity of timber increased as the moisture content decreased below 18%. Moreover, the bending strength was higher in three point bending tests compared to the four point tests for all timber species considered. The study also revealed that timber records its highest stiffness value as it approaches dryness.

Additionally, Ferreira et al. [34] underscored that the tensile strength of wood increases with decreasing moisture content below the fiber saturation point and is influenced by factors such as grain orientation and fiber characteristic [7, 11, 70]. The experimental investigation and numerical simulation conducted on pine and ash woods showed that the tensile strength is varied with the direction of the applied load, with different stress values and failure patterns observed for the parallel and transverse directions to the grain [24, 71, 72].

These findings underscore the intricate relationship between moisture content, grain orientation, and mechanical properties of timber [5, 46, 60, 73], providing valuable insights into its behaviour under external loads and its suitability for diverse structural and functional purposes.

A. Strength Properties

The strength properties of timber are crucial for assessing its suitability in load-bearing applications such as construction and engineering [2, 7, 74–75]. The strength properties of timber are highly anisotropic and affected by age, location within the tree, and structural imperfections. This results in considerable variability in mechanical properties, often referred to as random spatial variability. The scatter of timber elastic properties can significantly impact the local stress state and failure probability under external loading, an aspect that has received less attention than the scatter of strength. As reported on the pure tensile tests on clear timber, the mean strength of timber has been found to be inversely proportional to its volume due to the size effect on strength [4, 8, 76–77].

B. Stiffness Properties

Timber is a natural unidirectional fiber composite that exhibits highly anisotropic properties and influenced by age, location within the tree, and load history. Recent studies have highlighted the significance of longitudinal spatial variability in the elasticity of timber, particularly in relation to bending tests, and have incorporated experimental results into stochastic models with orthotropic elasticity. Stiffness properties of timber are crucial for understanding its behaviour under load and its structural performance [7, 65, 76–79]. The variability in mechanical properties has significant implications for the response of timber structures under external loading.

Furthermore, the classification of the bending strength of timber is essential for structural design and performance assessment [7, 74, 79]. Strength classification of timber is based on the characteristic values derived from test data, including mechanical properties, dimensions, moisture content, and wood density. The adoption of Eurocode 5 has prompted efforts to develop strength classification of timber species in various regions, aiming to align with international standards and enhance timber design practices [80, 81]. These efforts reflect a broader recognition of the significance of stiffness properties in timber for ensuring structural stability and safety.

C. *Workability and Machinability*

The significance of understanding the physical and mechanical properties of different timber species is essential to facilitate their selection for specific end-uses, thereby increasing the lifetime of the final product. This underscores the significance of considering the workability and machinability of timber in the decision-making process for selecting the most suitable timber species for a particular application. Workability and machinability are crucial factors in determining the usability of timber in manufacturing and construction processes. The ability of timber to be easily shaped, cut, and joined directly impacts its processability and adaptability in various applications [10, 82, 83].

V. Factors Influencing Properties of Timber

The properties of timber are influenced by various factors such as tree species, growth conditions, age, and wood processing techniques [5, 8, 18, 19]. For instance, basic wood density and initial moisture content are crucial for structural timber applications, with density showing an increasing trend with tree height. Additionally, the quality of finishing of timber have been reported to have significant impact on the physical properties including shrinkage and water absorption ability. Hence, the reliability, usability and the overall quality of timber are shaped by a combination of inherent characteristics and external treatments. It is therefore essential to consider these factors when evaluating and selecting different timber species for practical application [8, 43, 84].

A. *Tree Species*

Numerous studies have been conducted in Nigeria to evaluate and characterize different species of timber for structural purposes. Adekunle et al. [18] investigated the physical and mechanical properties of Ayinre (Albizia coriaria), Aga (Musanga cecropioides), and Orin dudu (Anogeissus leiocarpus) timber species in Abeokuta, Nigeria. Beam specimens of various dimensions were prepared for bending strength and modulus of elasticity tests, and evaluated the physical and mechanical properties in accordance with relevant standards.

Likewise, Oyediran et al. [19] investigated the mechanical properties of five timber species - Gmelina arborea, Tectona grandis (Teak), Terminalia superba (Afara), Ayin (Anogeissus leiocarpus), and Acacia (Robinia pseudoacacia) - to determine their suitability for constructing long-span roof trusses. These species were sourced from the southwestern Nigeria. Their suitability was evaluated in terms of the mechanical properties - bending strength, compressive strength, shear strength, tensile strength, modulus of elasticity, modulus of rupture, and density.

These studies provide valuable insights into the physical and mechanical properties of specific timber species, shedding light on their suitability for various applications and their performance under different conditions [85].

B. *Growth Conditions and Age*

Growth conditions and age significantly influence the physical, morphological, and mechanical properties of timber. Studies have found that wood property values do not necessarily continue to increase with age after reaching the age of demarcation between juvenile and mature wood. It has also been reported that the mechanical and anatomical properties of plantation-grown eastern cottonwood and loblolly pine improved markedly with age, with a significant increase in modulus of elasticity from early juvenile wood to late mature wood [4, 61]. The age of demarcation between juvenile and mature wood varied by species and property ranging from 13 to 20 years emphasizing the importance of age in understanding timber properties.

These studies underscore the importance of considering growth conditions and age when evaluating the properties of timber, as they have a substantial impact on the physical, morphological, and mechanical attributes of timber [5, 62].

C. *Wood Processing Techniques*

Wood processing techniques play a crucial role in determining the physical, morphological, and mechanical properties of timber [62, 86]. Sawing, drying, and treatment are key processes that significantly influence the characteristics and performance of wood. Numerous studies have highlighted the impact of chemical modification on the physical and mechanical properties of wood. The research emphasized the potential of color measurement for predicting the strength of thermally treated wood, as well as the influence of different aldehyde-based agents on tensile strength. These studies underscore the significance of wood processing techniques in shaping the properties and performance of timber [8, 10, 74, 87], emphasizing the need for comprehensive understanding and application of manufacturing processes to enhance or alter timber characteristics.

VI. Applications and Uses of Major Timbers

Timber is widely utilized across various industries due to its diverse applications and use [3, 31, 74, 88]. In the construction industry, timbers such as Douglas fir, southern pine, redwood, maple, and white oak are commonly used for structural applications due to their resistance to acids and thermal insulating properties [31, 89]. Furthermore, timber is employed in the construction of chemical plants and vessels for chemicals due to its resistance to deterioration by chemicals. However, it is noteworthy that wood may contain irregularities and imperfections that can affect its mechanical properties, such as knots, bark pockets, and splits developed during the seasoning process. Grading systems exist to indicate the quality of lumber, with high ratings or specifications of 'clear' indicating lumber free from visual defects [67, 85].

In the furniture making industry, various timber species like Madhuca longifolia, Albizia saman, Hevea brasiliensis, Tectona grandis, and Toona ciliata are utilized for different purposes such as furniture, flooring, and musical instruments due to their specific physical and mechanical properties. Understanding these properties is crucial in selecting the most suitable timber for specific applications. Overall, the diverse applications and uses of major timbers across industries highlight their versatility and suitability for specific purposes [43, 58].

VII. Sustainability and Environmental Impacts

Sustainability and environmental impact are crucial considerations in timber usage [2, 7], given the potential ecological implications. Sustainable forestry practices, such as forest certification programs, play a significant role in regulating timber harvest areas to ensure the longevity of forest resources.

Furthermore, timber's low energy production processes and environmentally friendly nature make it an efficient building material with attractive mechanical properties, such as high specific strength and stiffness. However, the mechanical properties of timber are inherently highly variable due to factors such as random spatial variability (RSV) and moisture content. Research has focused on understanding and modeling the effect of RSV on clear timber mechanical properties, with the development of size effect models and the use of the Monte Carlo method to obtain stochastic responses. This emphasizes the need for a comprehensive understanding of timber's mechanical behaviour and variability to ensure sustainable and environmentally conscious usage in construction and other applications [7, 17, 38, 90].

VIII. Future Research Directions

Future research in the study of timber properties should focus on advancing the understanding of the mechanical behaviour of timber, particularly in relation to its highly variable properties [7, 12, 74, 91, 92]. There is a need to further explore the probabilistic and stochastic approach to analyzing timber structures. This involves modeling the effect of random spatial variability (RSV) on clear timber mechanical properties, developing experimental characterization of RSV for clear timber, and creating a stochastic finite element framework for random response assessment of clear timber components. Additionally, the importance of understanding the physical and mechanical properties of various timber species for different end-uses cannot be overemphasized [39, 72, 93]. Hence, future research should focus on providing guidance for objective assessment of timber suitability based on end-use property classification.

These future research directions will contribute to expanding the knowledge and utility of major timbers, paving the way for innovative applications and advancements in measurement techniques.

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