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Research paper

EMPIRICAL ANALYSIS OF FIBER REINFORCED SHOTCRETE

Sead Abazi[1], Bulent Suloodja[2]

Abstract

Reinforced shotcrete has been used for 40 years and is widely used in both construction and mining engineering. In recent years, the use of fiber-reinforced concrete has increased significantly, with significant progress being made in terms of quality and application techniques. Due to its advantage in improving certain material properties, fiber-reinforced shotcrete is widely used in tunnel construction, industrial flooring and airport runways, slope protection, and in mining tunnels, fiber-reinforced shotcrete is used. The use of this type of reinforced concrete has a number of advantages over other types of concrete. Using reinforced shotcrete provides a number of advantages. The economic advantages include: less labor, removal of ordinary reinforcement, a smaller layer for installation and saving time and material. While the technical advantages include increased load-bearing capacity, higher initial strength, smaller rebounds and a smaller amount of installation. From the analysis of time savings in the process of installing shotcrete with and without fibers, it appears that up to several hours of savings are achieved with the process of building shotcrete reinforced with fibers. A similar example is the application of shotcrete with an area of 30 m². The entire process using steel mesh takes 11.5 hours, while with fibers, 7.5 hours. From this it can be seen that for only 30 m², 1/3 of the total time is saved by using shotcrete reinforced with one of the fibers. This combination is combined in the unit price with using shotcrete reinforced with steel mesh and fibers. Unlike ordinary shotcrete, the strength decreases with the appearance of the first crack, while in reinforced shotcrete this is not the case because the stresses on the fibers are transferred to the adjacent sections. This means that if there is a larger amount of fibers in the concrete mixture, then it has the ability to carry greater loads. This has been confirmed by a series of experiments, which confirm the durability and flexibility of reinforced concrete reinforced with steel fibers.

Key words: S*hotcrete, fibers, strength, tunnel construction, flexibility*

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1. INTRODUCTION

Concrete has many advantages, which makes it by far the most used and most important construction material. However, like other materials, concrete also has disadvantages, such as: low tensile strength, brittle fracture, low specific strength, low ductility, need for formwork, long curing time, appearance of cracks, etc. Gradually, work is being done to improve the physical and mechanical properties of concrete and various additives are being found that will improve the characteristics and performance of this material. Various additives, synthetic and fiber fibers, mineral additives, and others are being added. So today, highly technologically developed types of concrete are being produced, such as reinforced concrete. Reinforced concrete, since ancient times, was used as a binding material. Thus, straw was used as a binder for clay, and horsehair for gypsum. In the 20th century, intensive technological development and development in engineering practice occurred. But it must be admitted that reinforced concrete is very rarely used alone and its use in combination with screws, reinforcing bolts, iron bars or steel structures further complicates the problem of analyzing the contribution of the support. The first tests on reinforced concrete were made in 1874 by A. Beranda, by adding steel scrap to the concrete. After the publication of the results by the American scientist Porter, the world began to work intensively on this topic.

2. FIBRE REINFORCED SHOTCRETE

Reinforced shotcrete has been used for 40 years and is widely used in both construction and mining engineering. In recent years, the use of fiber reinforced shotcrete has increased significantly, and significant progress has been made in terms of quality and application techniques. Due to its advantage in improving certain material properties, fiber reinforced shotcrete is widely used in tunnel construction, industrial floors and airport runways, slope protection, and in mining tunnels, fiber reinforced shotcrete is used. There are a number of advantages to using this type of reinforced concrete compared to other types of concrete.

2.1. Steel fibre reinforced shotcrete

Steel fibres are often used as reinforcement of shotcrete. To select the appropriate shape of the steel fibres, their tensile strength and length-to-diameter ratio have to be considered in line with the design requirements. The following improve-ments of the shotcrete can be expected by application of steel fibres:

- increased ductility;
- higher compressive and tensile strength;
- reduced crack formations.

Figure 1. Steel fibre

The amount of steel fibres in the final concrete mix should be in the range of 30 - 90 kg/m³. Because of the loss by rebound during the application of shotcrete, 35 – 120 kg/m³ of fibres should be included in the basic mixture. Steel fibres with a high length-to-diameter ratio are essential for efficient reinforcement. However, the pro-cessing is difficult with such steel fibres. In current practice, bundles of 30 to 50 fibres are added to the shotcrete mix. The wrapping of these bundles is water-soluble, which leads to a dispersion of the fibres in the mixture at the beginning of the mixing process. Steel fibre reinforced shotcrete has economic benefits if the required project specific static values are equivalent to the use of shotcrete lining with one- or multi-layered reinforcements (steel meshes). It can also be applied as a subsequent rein-forcement. Figure 2 shows the variations of compressive strength against the defor-mation for shotcrete with different contents of steel fibre reinforcements (plate loading test) [1].

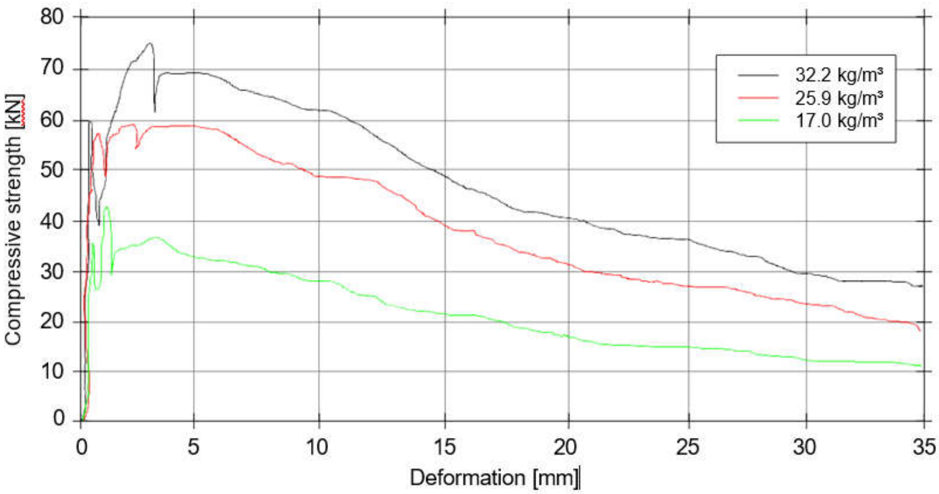

Figure 2. Compressive strength versus deformation: plate loading tests on shotcrete with different amount of steel fibers

In Tabela 1 shows experimental results for Young's modulus and Poisson's ratio obtained from uniaxial compressive tests on three steel fibre reinforced (30 kg/m³) shotcrete samples at different curing times. The UCS increases with time, but elastic properties (Young's modulus and Poisson's ratio) do not show a systematic variation.

Table 1: Uniaxial compressive test on steel fiber reinforced shotcrete samples

Sample No	Curing (days)	Compr. Strength (MPa)	Elastic properties	
			Young's modulus (MPa)	Poisson's ratio
			E	v
1	1	16.2	-	-
2	1	18.1	14000	0.42
3	1	18.3	11000	0.19
1	3	23.4	-	-
2	3	18.3	12000	0.28
3	3	22.9	8000	0.16
1	7	28.5	-	-
2	7	23.2	16000	0.22
3	7	25.7	14000	0.17
1	28	32.8	14000	0.21
2	28	27.2	17000	0.29
3	28	31.5	10000	0.15

2.2. Synthetic fibre reinforced shotcrete

Synthetic fibers are additives that improve the properties of concrete and can completely replace steel mesh, or steel fibers. This type of fiber is new and was first used in 1990 to compete with steel fibers. Their positive and negative properties have yet to be investigated. Synthetic fibers, just like steel fibers, can be used in combination to improve properties and eliminate microcracks.

Synthetic fibers have similar characteristics to other types of fibers, but they also have something additional that makes them a step ahead of others:better processing:

- higher density,
- higher adhesive tensile strength,
- increased chemical resistance,
- improved thermal behaviour,
- improved quality of thin lining,
- higher early / final strength,
- does not damage the rubber hoses of the jet spray pump,
- compared to steel fibers, they have a low bulk density, meaning that 5-6 times less per m^3 is added to the mixture than other fibers, and this feature facilitates field work.

Figure 3. Synthetic fibre

Synthetic fibers, although new, show good results in all aspects. In any work, one of the most important things is the environment, and by using these fibers, it is protected and there are no major negative impacts on the environment. In addition to protecting the environment, the use of synthetic fibers also saves financial resources: a thinner layer of shotcrete, less rebound losses, etc. And by using this type of reinforcement of reinforced concrete, the safety of contractors is also increased because when installing shotcrete with macrosynthetic fibers, the nozzle is not under a rock mass that is not yet stable [1].

There are two types of synthetic fibres:

1. Synthetic macro fibres,
2. Synthetic micro fibres.

Synthetic macro-fibres have lower Young’s modulus values than steel fibres. They are very effective in preventing cracks in the shotcrete and reducing the crack width. The shotcrete becomes more ductile and shows better corrosion protec-tion when these fibres are used. The Young’s modulus of synthetic micro-fibres is even lower than those of synthetic macro-fibres. This type of fibres can reduce the shotcrete shrinkage in the early stage of the hydration process. The application of synthetic micro-fibres is beneficial when there is a potential for heat exposure, e.g. fire. If the temperature increases up to 160 °C, the polypropylene fibres melt inside the concrete forming new cavities, which help to release additional pressures. Therefore, explosive spalling of concrete can be re-duced. This type of reinforcement is often used for the renovation of tunnels. After 28 days this type of reinforced shotcrete shows a UCS in the range of 44 - 61 MPa.

Table 2: Data for synthetic fibers

	Macro-fibres	Micro-fibres
Amount	3 - 10 kg/m³	0.6 - 2 kg/m³
Length	40 - 60 mm	5 - 15 mm
Diameter	0.4 - 1 mm	0.015 - 0.2 mm

2.3. Mixing of shotcrete with fibers

The most important part in relation to ordinary shotcrete and shotcrete with fibers is the dosing and mixing of the fibers into the concrete mix itself. Many details in this work, so that there is no stopping of the construction equipment and clumping of the material to be built. In order to avoid changes, special machines have been produced that mix the concrete mix and various fibers as reinforcements. It is not only the hose that transports the mix from the machine to the nozzle, but also in the network itself, clumping of the reinforced concrete can be avoided.

The wet method is mainly used for mixing the concrete mix with fibers because in the dry method the bounce is very bad. But it does not mean that the dry method is excluded. In the dry method, the fibers are first placed in a drum so that there is no clumping of the material. The slurry is moved under pressure to the nozzle. In the meantime, the aggregate and cement are mixed, and then water is added. When using a wet method for spraying concrete with steel fibers, the fibers are poured into the nozzle and mixed with the concrete mixture before the nozzle [2]. The same can be done in the concrete production plant

Regardless of which method is used, there should be a correct distribution of the concrete on the concrete surfaces and adequate mixing of the concrete with the fibers before it is applied to the surface. Mixing the fibers with the concrete mass should pay attention to:

- the fibers should be added slowly to prevent clumping of the material;
- the fibers should not be twisted to prevent clumping of the material, which in turn causes clogging in the installation pump;
- to place the electron so that the material does not clump;
- the fibers can cause a risk of kickback, so when installing, mechanized nozzles are used, paired from a distance and others.

Figure 4. Machine for applications of Steel Fiber Reinforced Concrete

3. ANALYSIS OF FIBER REINFORCED SHOTCRETE

Using fiber reinforced shotcrete provides a number of advantages. The economic advantages include: less labor, removal of ordinary reinforcement, a smaller layer for installation and saving time and material. While the technical advantages are: increased load-bearing capacity, higher initial strength, less rebound and a smaller amount of installation. Time savings is one of the listed factors [3].

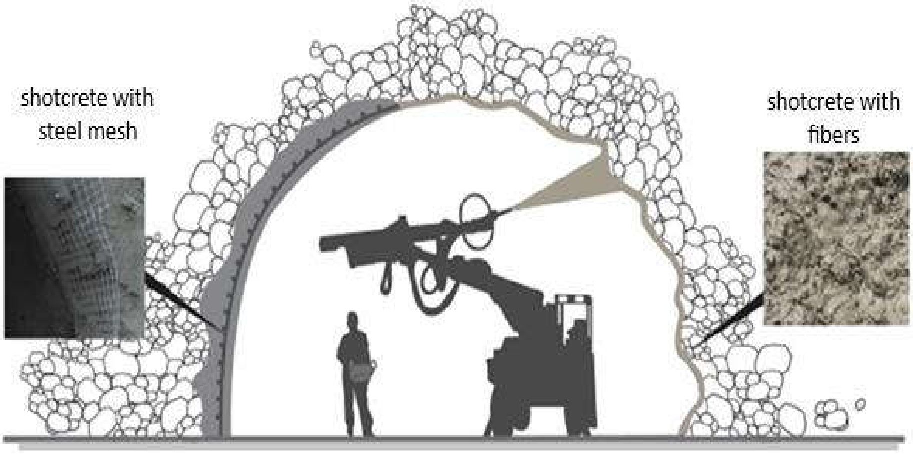

Figure 5. Shotcrete with steel mesh and with fibers

I cannot give examples from my country because this type of concrete is not used. The popularity of shotcrete reinforced with various types of fibers can be gauged from how widely it is used in Australia, and this can only help to shed some light on the full picture of its applications. Of the 650,000 m³ of shotcrete installed, 500,000 m³ is fiber-reinforced shotcrete. Macrosynthetic fibers are the dominant form of reinforcement, with a small number of mines continuing with steel fibers, and a minority also including microsynthetic fibers for control of rebound and fall-outs immediately after spraying. The versatility of fibre reinforced shotcrete, both in terms of structural capacity and mixture design, allows miners a higher degree of adaptability in the implementation of ground control and development of underground infrastructure than is possible using any of the currently available alternatives. The direct material and labor costs associated with initial ground control using the fibre reinforced shotcrete and bolt system are about 20% higher than for alternatives such as mesh and bolts. When the superior speed, versatility, efficacy, durability, and safety of fibre reinforced shotcrete are considered, however, their combined economic advantage make this system of ground control the most attractive presently available in the majority of circumstances [4].

From the analysis of time savings for the process of installing shotcrete with and without fibers, the conclusion is that several hours are saved with the process of installing shotcrete reinforced with fibers. A similar example was made in Australia for the application of shotcrete with a surface area of 30m². The entire process using steel mesh took 11.5 hours, while with fibers 7.5 hours. From this it can be seen that for only 30m² 1/3 of the total time was saved by using shotcrete reinforced with one of the fibers. This comparison is transformed into the total cost of using shotcrete reinforced with steel mesh and fibers. From Figure 6 it can be concluded that by increasing the thickness of the shotcrete layer, the cost of shotcrete reinforced with steel fibers decreases [3].

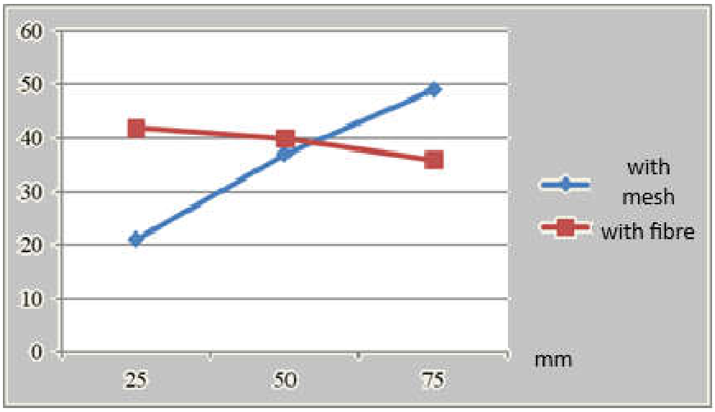

Figure 6. The cost of shotcrete reinforced with steel fibers and thickness of the shotcrete layer

4. CONCLUSION

Due to its advantage in improving certain material properties, fiber-reinforced shotcrete is widely used in tunnel construction, industrial flooring and airport runways, slope protection, and in mining tunnels, fiber-reinforced shotcrete is used. The use of this type of reinforced concrete has a number of advantages over other types of concrete. The economic advantages include: less labor, removal of ordinary reinforcement, a smaller layer for installation and saving time and material. While the technical advantages include increased load-bearing capacity, higher initial strength, smaller rebounds and a smaller amount of installation. From the analysis of time savings in the process of installing shotcrete with and without fibers, it appears that up to several hours of savings are achieved with the process of building shotcrete reinforced with fibers.

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Research paper

PHOTOMETRIC ANALYSIS OF HOMOGENIZED X-RAY IMAGES IN DETERMINING THE MECHANICAL PROPERTIES OF WOOD: PRELIMINARY RESULTS

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Abstract

Previous research demonstrated a link between wood strength and brightness intensity in X-ray images. Wood samples were subjected to compression testing along and across the grain, with X-ray imaging performed on the same specimens before the mechanical tests. Differences in the brightness of X-ray images of test specimens were clearly noticeable, both in relation to the type of sampled wood and depending on the specific alignment of X-ray beams relative to the direction of wood fibers in the test specimen. Because wood has an anisotropic structural composition, it is expected that the X-ray image of the tested sample would exhibit uneven brightness. Photometric analysis of the X-ray image using computer software allows for assigning appropriate mechanical properties to each point on the image via x, y, v parameters. However, since an individual light point cannot represent the cumulative mechanical properties of the sampled test specimen, it is clear that the task at hand also includes the need for homogenizing the X-ray image. This is achievable through the program's three-dimensional approximation capabilities. The creation of a tonal grayscale through image homogenization would enable the alignment of mechanical strength parameters with brightness intensity values. This process would effectively represent the overall mechanical potential of the wood sample as a cumulative result, linking the homogenized brightness of the X-ray image with the wood's strength characteristics.

Key words: *Photometric, X-ray, OsiriX, Tonal gray scale, Equalization, Wood*

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1. INTRODUCTION

The concept for this research arose from the necessity of restoring wooden structures in architectural objects of cultural and historical significance, where such work is governed by specific regulations that require a specialized, non-invasive diagnostic approach. This methodological framework is also recommended for the restoration and reconstruction of other structures of potential heritage value, as each may be regarded as a monument to the era in which it was created. The procedures for such restoration efforts are outlined in a document adopted by ICOMOS during the General Assembly held in New Delhi in 2017. This document details the principles for the conservation of wooden architectural heritage, emphasizing the protection of their authenticity and structural integrity [1, 2].

Identifying the most stressed points of the structure and detecting signs of degradation and damage in wood are essential prerequisites for developing an appropriate rehabilitation plan. The non-destructive nature of the diagnostic process necessitates in situ examination. Therefore, this study aimed to establish a reliable and easily applicable non-destructive diagnostic method. The use of X-rays was considered for this purpose, as their orientation can be aligned either parallel or perpendicular to the wood grain, analogous to laboratory-based static mechanical testing [3, 4].

In our previous research involving X-ray application, tabulated strength values of experimental wood samples were used, and it was confirmed that samples with higher strength yielded brighter X-ray images, validating the analogy. The harmonization of mechanical and radiographic parameters now required standardized mechanical calibration of the wood specimens and computerized objectification of image brightness. This methodology was supported by the capabilities of the OsiriX software, indicating its suitability for the intended analysis [5, 6].

2. METHODOLOGY

X-ray testing was conducted on wood samples from diffuse-porous hardwoods—beech (Fagus sylvatica) and poplar (Populus spp.); ring-porous hardwoods—black locust (Robinia pseudoacacia) and oak (Quercus spp.); and softwoods—pine (Pinus spp.) and silver fir (Abies alba), including a control group of samples from horse chestnut (Aesculus hippocastanum). To ensure X-ray image homogenization, the specimens were cut to dimensions of 20 × 20 × 40 mm. These samples were prepared similarly to those used in standard compressive strength tests, with the longitudinal axis aligned with the grain direction. The longitudinal plane intersecting the sample perpendicularly to its length was parallel to the grain lines and considered the axial plane, while the planes intersecting the two longitudinal sides at right angles represented the tangential and radial planes [4, 7, 8].

A second set of specimens had a transverse profile, with the axial plane intersecting the longest dimension at a right angle. Testing was carried out using a medical-grade X-ray machine operating within a range of 40–125 kV and 0.50–360 mA/s, similar to those used in clinical diagnostics, where upper limits are typically 100 kV and 70 mA/s. Each sample set was imaged using a current voltage of 37 kV and a strength of 70 mA/s. Following radiography, standard compressive strength testing was also performed on the same specimens.

The brightest X-ray images were observed in the ring-porous hardwoods, which also exhibited the highest measured compressive strength. Progressively lower brightness was observed in the diffuse-porous hardwoods, with the lowest intensity seen in the softwood samples. The brightest images in all test groups were obtained when X-rays were directed along the axial plane; lower brightness was noted when X-rays were directed in the radial direction, and the lowest when directed tangentially, corresponding proportionally to the measured compressive strengths [9, 10, 11] (see Appendix).

3. RESULTS

3.1. Photometric Analysis:

Photometric analysis of the X-ray images represented the final step in the harmonization of mechanical and radiographic parameters. This was performed using OsiriX software, which is widely used in medical diagnostics. Its three main operational components—Database Window, Viewer Window, and 3D Volume Rendering—enable the importation of X-ray datasets, 2D/3D image viewing, and image manipulation within the study list environment [6, 11, 12].

Of particular importance is the drop-down menu tool *WW/WL* (Window Width/Window Level), used to adjust image brightness and contrast. The software's CLUT (Color Look-Up Table) module offers additional tools for selecting and adjusting color ranges, which can enhance operational precision.

Due to the heterogeneous and anisotropic nature of wood—where mechanical properties vary according to the direction of grain flow, leading to image brightness variability—the software tools especially valuable for structural wood visualization include *Orientation* (for spatial positioning relative to horizontal, frontal, and sagittal planes) and *Thick Slab* (for deepening cross-sectional views) [13].

Key tools for image homogenization and analysis include:

- **ROI Tools** (Region of Interest): Enable targeted image analysis.
- **Repulsor Tool**: For manipulating defined ROIs.
- **Selector Tool**: Allows grayscale and color adjustments within selected ROIs.
- **Propagate Tool**: Applies defined ROIs across all cross-sections.
- **Region Growing**: Expands areas around selected points, useful for diagnosing damage and degradation in structural wood elements.
- **Filters**, particularly **Convolution Filters** in the 2D Viewer menu, used in bone diagnostics, offer potential applicability here by producing 3D renderings with enhanced contrast.

The **3D Volume Rendering** module enables each point in the image to be assigned corresponding mechanical properties based on its x, y, z coordinates. However, due to the anisotropic nature of wood, a single point cannot fully represent the collective mechanical properties of the entire specimen, even though dimensional uniformity helps in achieving a certain level of homogenization.

Therefore, X-ray image brightness homogenization must ultimately rely on additional operational tools such as **Engine Tools**, which support Ray Cast and 3D Texture applications.

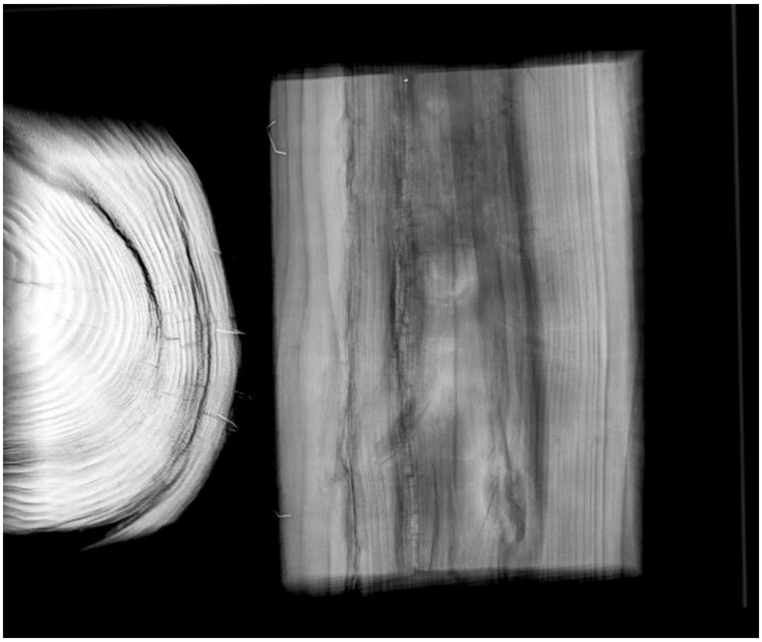

Figure 1. X-ray of a log of wood

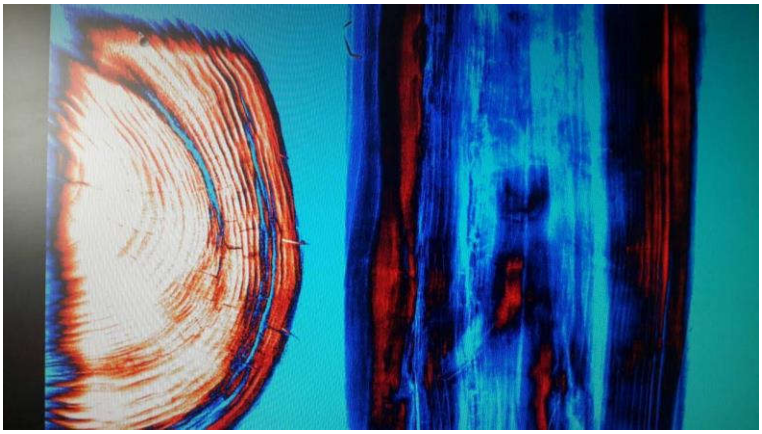

Figure 2. X-ray image through OsiriX software - example

4. CONCLUSION

The harmonization of mechanical and photometric parameters should result from a comprehensive evaluation of the material's mechanical properties.This approach significantly enhances the diagnostic reliability and practical value of the material evaluation process. Future work could focus on refining this diagnostic method for larger structural elements and validating it through in situ testing.

ACKNOWLEDGMENTS

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APPENDIX

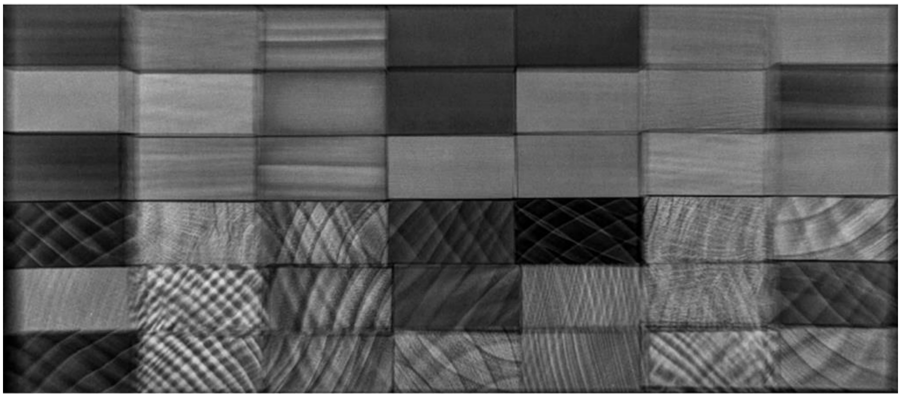

Figure 3. Mosaic.

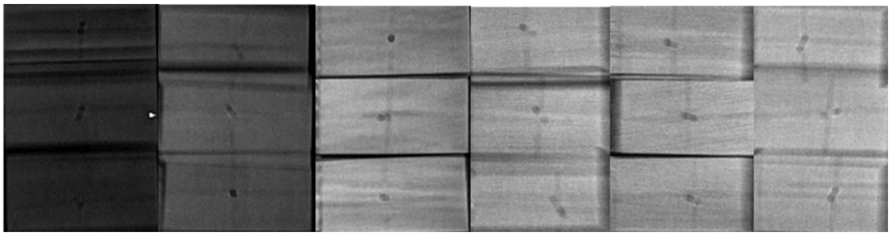

Figure 4. Zebra.

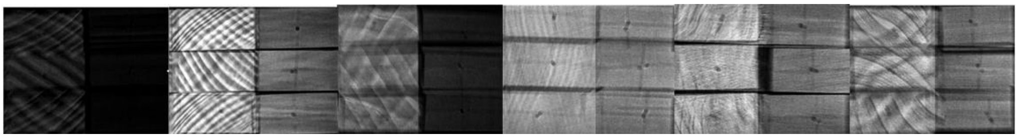

Figure 5. Tonal palette.

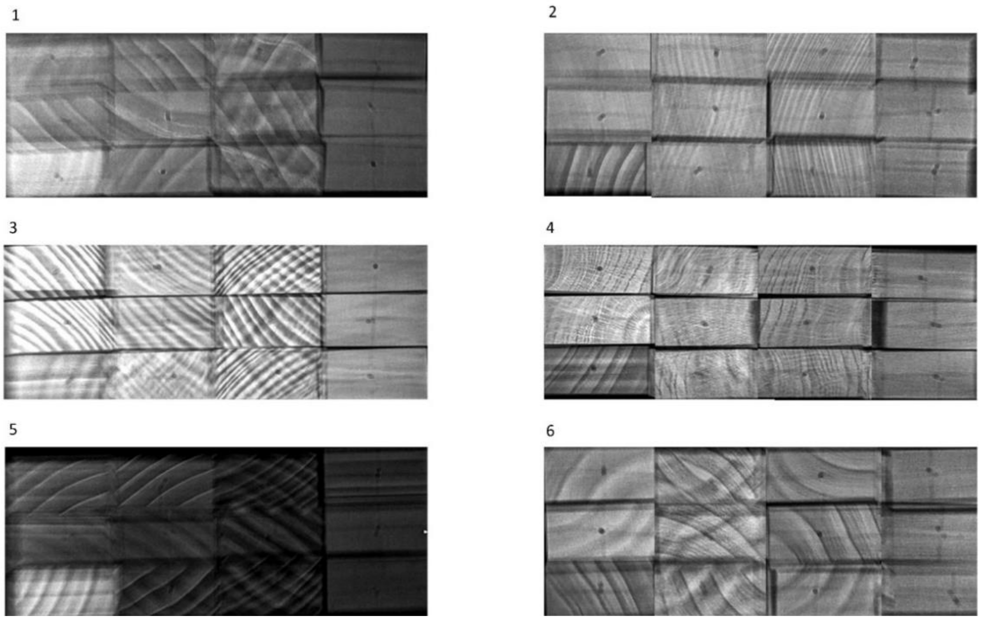

Figure 5. Wood samples. 1.poplar; 2 beech; 3 pine; 4.oak; 5.fir; 6. acacia.

Table 1. Values of compressive stresses determined on test sample in the calibration procedure of the stress-sound wave application method.

	Softwood					Hardwood					
						Ring Porous				Diffuse Porous	
	Spruce 1	**Fir 1**	**Fir 2**	**Pine 1**	**Pine 2**	**Oak 1**	**Oak 2**	**Black Locust1**	**Black Locust2**	**Beech 1**	**Beech 2**
Length (mm)	39.72	40.2	39.13	39.37	39.1	39.04	39.3	39.32	39.3	39.48	39.57
Width (mm)	20.18	20.16	19.96	20.12	19.93	19.92	19.86	19.79	20.27	19.94	19.8
Thickness	/	/	/	/	/	/	/	/	/	/	/
Compressive force—transversal (lateral)	3113	1883	1648	13129	4979	4149	4621	5839	4736	4624	4760
Compressive force—axial (transverse)	/	/	/	/	/	/	/	/	/	/	/
Transversal stress	3.9	2.3	2.1	16.6	6.4	5.3	5.9	7.5	5.9	5.9	6.0
Axial stress	/	/	/	/	/	/	/	/	/	/	/
Length (mm)	/	/	/	/	/	/	/	/	/	/	/
Width (mm)	19.75	10.86	19.94	20.08	20.29	19.84	19.84	19.93	20.02	19.82	19.96
Thickness	19.86	19.85	19.89	20.09	20.08	19.77	19.79	19.9	20.12	19.19	19.9
Compressive force—transversal (lateral)	/	/	/	/	/	/	/	/	/	/	/
Compressive force—axial (transverse)	19,550	2116	21,212	34,214	27,739	24,223	27,742	39,241	37,842	31,563	29,053
Transversal stress	/	/	/	/	/	/	/	/	/	/	/

Table 2. Values of bending stress determined on test samples in the calibration procedure of the stress sound wave application method.

	Softwood					Hardwood					
						Ring Porous				Diffuse Porous	
	Spruce 1	**Fir 1**	**Fir 2**	**Pine 1**	**Pine 2**	**Oak 1**	**Oak 2**	**Black Locust1**	**Black Locust Acacia 2**	**Beech 1**	**Beech 2**
h [mm]	19.74	19.86	19.84	20.01	19.78	19.89	19.85	19.79	20.1	19.88	19.91
b [mm]	19.72	19.83	19.88	20.11	19.91	19.88	19.84	19.94	20.06	19.92	19.81
Bending strength MPa [N/mm^2]	88.9	79.9	71.6	132.9	102.8	91.09	124.5	86.4	170.3	169.8	128
Modulus of elasticity MPa [N/mm^2]	6108	8137	7905	11567	7448	6792	8232	11020	14788	11987	9145
Force max. [N]	1627	1488	1334	2572	1907	1706	2316	1605	3288	3182	2393
Deflection max. [mm]	13.85	11.78	10.28	9.39	17.95	16.58	15.04	10.27	14.5	12.64	16.67
h [mm]	19.74	19.83	19.89	19.98	20.03	19.85	19.94	19.9	10.07	19.9	19.8
b [mm]	19.78	19.79	19.86	19.92	20.14	19.83	19.85	19.92	20.31	19.84	19.8
Bending strength MPa [N/mm^2]	84.1	81.3	76.9	152.1	119.1	103.3	105.8	200.9	185.2	135.9	133.3
Modulus of elasticity MPa [N/mm^2]	8784	8262	7304	12,778	10,337	7722	6882	15,175	13,920	10,315	9722
Force max. [N]	1544	1506	1438	2880	2291	1921	1987	3773	3607	2542	2464
Deflection max. [mm]	12.58	11.26	11.06	18.21	12.6	17.36	20.05	13.16	14.74	11.61	12.59