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Determination of Stiffness and Hardness of Glasses by using Acoustic Waves Testing

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***Abstract*—*In this study we sought to develop a non-destructive test that uses the propagation of acoustic waves to characterize the stiffness and hardness of flat glasses. For this purpose, three different glass samples were investigated by using acoustic waves resulting from the impact caused by a steel sphere in free fall on the samples surface. As a result, it was found that the glass samples have different vibration frequency and this behavior is associated to the Young's modulus and microhardness, values. The values calculated by the ultrasonic transmission method indicated that the increase in stiffness is related to the appearance ofamplitude peaks in the acoustic signal of the samples, attesting to the possibility of the method for characterizing the mechanical properties of glasses used in civil building.*

I. INTRODUCTION

Flat glass, known as float glass, stands out in the building market due to the growth of glazed areas that represent a characteristic of modern architecture. In contrast to the architectural beauty, the increase in glazed areas leads civil building professionals to several questions about safety and the increase in internal temperature in buildings, which in turn, favors greater consumption of electricity with refrigeration equipment.

Float glass is a soda-calcium silicate glass, transparent, colorless or colored in its mass, with parallel and flat faces. This type of glass is obtained by continuous melting and solidification inside a bath of molten metal [1]. Besides to being applied in civil building, they are also used as a basis for obtaining other types of commercial glasses. The chemical compositions of colorless, smoked and green glasses are well known, with only small variations found in their main constituent elements, such as: 68-75% SiO_2,10.2-17% CaO, 6-12.4% Na_2O, 0-4% Al_2O_3, 0-5.5% MgO and 0-3% K_2O[2-6].

With regard to colorless glass, it has generally low percentages of Fe_2O_3 or the absence of this oxide among its main constituent elements, but additions between 0.25% and 0.65% can favor the coloring of the smoked glass [4, 6, 7].The greenish color can be obtained by keeping the percentage range of Fe_2O_3 and adding 1% cerium oxide (CeO_2) and 1% titanium oxide (TiO_2) [3]. Values between 0.002% and 0.06% of CrO_2 are also responsible for the coloring of some green glasses [8].

The colors varietyof float glass allow its use in situations where it is desired to reduce the entry of light into buildings, controlling solar radiation, since part of the radiation will be reflected to the external environment and the other part will be absorbed by the glass [8].

It is important to know some properties when using float glass. Among them, the following stand out: flexural strength, hardness, electrical resistivity and optical absorption.These properties provide important information on glass performance in different usage situations [5, 9, 10, 11]. However, knowledge of these properties is still insufficient to characterize glasses more comprehensively, being necessary to carry out studies on dimensional analysis, mechanical shock resistance, thermal shock resistance, fragmentation and safety tests.

The majority of mechanical tests for the characterization of glass are destructive, in other words,they damage the investigated samples. These tests also require more time and cost to acquire the results and to produce samples that will be destroyed. On the other hand, there are non-destructive tests capable of investigate a material without having to destroy it.For example, acoustic wavespropagated through a ceramic material can provide important information about its mechanical characteristics and structural integrity [12,13]. In this way, some studies have shown a simple and accessible methodology to investigate the mechanical properties of materials with acoustic waves. [14, 15].

The development of a non-destructive testing and low-cost methodology were the main motivators of this study that aimed to investigate the use of acoustic waves as an alternative to characterize the hardness and stiffness of glasses used in the civil building.

II. EXPERIMENTAL

2.1 Samples characteristics

To perform the acoustic waves testing, three samples of window glasses were commercially acquired in a common glazing company. The glasses were one colorless,one smoked andone green.After cutting, the samples were weighted in an analytical balance with resolution equal to 0.001 *g* and their dimensions were measured using a digital caliper. All the samples had clean andsmooth surface. Moreover, they were free of flaws or cracks.The volume of each sample was calculated by the product:length (*l*) x width (*w*) x thickness (*t*). Table 1 shows the dimensions, weigh and volume for each glass sample.

The density (ρ) of the samples was calculated using Equation 1, which represents the ratio between weight (*W*) and volume (*V*). The calculated values were assumed to be uniform, since samples with constant inertia and homogeneous weightdistribution were considered.

Table. 1: Weight and Volume of glass samples

Glass	Weight (*kg*)	*l* (*m*)	*w* (*m*)	*t* (*m*)	Volume ($10^{-5} m^3$)
Colorless	0.207	0.2200	0.1050	0.0036	8.3160
Smoked	0.195	0.1999	0.0998	0.0037	7.3815
Green	0.193	0.1998	0.1000	0.0035	6.9930

$$\rho = \frac{W\ (kg)}{V\ (m^3)} \quad (1)$$

2.2 Mechanical properties byusing ultrasonic testing

In isotropic materials several mechanical properties can be calculate using the density (ρ) of material and ultrasonic longitudinal (V_L) and shear (V_S) wavevelocities[16-21]. Thus, Equations 1, 2 and 3 were used to determine the Young's modulus (*E*), Poisson's ratio (*v*) and microhardness (*H*) of the glass samples, respectively.

$$E = \rho V_S^2 \left(\frac{3V_L^2 - 4V_S^2}{V_L^2 - \rho V_S^2} \right) \quad (2)$$

$$v = \frac{V_L^2 - 2V_S^2}{2(V_L^2 - V_S^2)} \quad (3)$$

$$H = \frac{(1 - 2v)E}{6(1 + v)} \quad (4)$$

To measure the ultrasonic signals propagated through the glasses an electronic systemitter and detectorof longitudinal ultrasonic waves was previously developed. The signals were generated using a piezoelectric transducer with a diameter of 0.02 *m* and 125 *kHz* frequency, beingcaptured with another identical transducer. The measurements were made based on the transmission method [22, 23]. In this procedure, the transducers are placed at the ends of the samples (Figure 1). Bee honey was used as a couplant between the transducers and the glass surface.

The travel time, in microseconds (*ms*), between the emitted and received ultrasonic wave was measured on an oscilloscope screen(Tektronix TBS1062) and exported to OpenChoice Desktop program that is connected to the electronic system. Figure 2 shows a measurement of the longitudinal ultrasonic wavetravel time through the glass sample. The length measured between the centers of transducers was 0.18 *m*. This value was admitted as distance traveled by the ultrasonic wave.

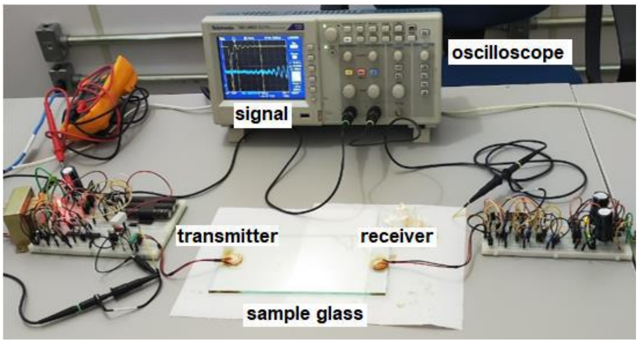


Fig.1:Transmission ultrasonic method

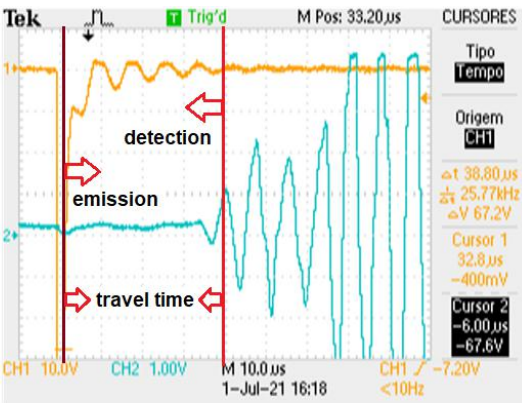


Fig.2: Travel time of ultrasonic wave through the glass

To calculate the velocity of longitudinal wave (V_L) the Equation 5 was used. In this equation, d = distance traveled by the ultrasonic wave and t= travel time through the sample. The mean value of V_L was obtained from three reproducible measurements that were performed by removing and repositioning the transducers at the ends of the samples.

$$V_L = \frac{d\ (m)}{t\ (s)} \tag{5}$$

The velocity of shear wave (V_S) was estimated by the relationships that exist between V_S and V_T for the glasses.In several studies it can be seen thatthe ratio between V_S and $V_T$for soda-lime glass is around 0.60 [5, 7,23]. This behavior is also observed in tellurium, lead, zirconia or boron glasses and also in fused silica glass [17, 18, 23,24]. Therefore, the shear velocity wave was estimated by Equation 6.

$$V_S = 0.6V_L \tag{6}$$

The values of V_L, V_S and ρ were used to determine the mechanical properties presented byEquations 2, 3 and 4. After that, the results were compared with the acoustic signals obtained in theglass samples.

2.3 Generation and acoustic signalscapture

For analyze the propagation of acoustic waves on the surface of the samples was used a free software. The Soundcard Oscilloscope software has been used in the study of acoustic wave propagated in different materials, such as ceramic brick, tiles, concrete and steel. In the present study, the samples were impacted witha stainless steel sphere (weight = 9 *g*, diameter = 12.7 *mm*) abandoned in free fall. To ensure that the sphere was always abandoned from the same position, a PVC tube with 0.02 *m* high and 0.0254 *m* diameter was used. The acoustic signals generated were captured with the Soundcard Oscilloscope software that represents a digital oscilloscope. Then, average acoustic signal for each sample was obtained from 20 measurements.

The amplitude of the signals measured (in the arbitrary unit a.u.) was investigated as a function of the acoustic wave propagation time in therange between 0 and 30*ms*. Anearphone stereo Plug P2 was used as a receiver for the acoustic signals. The earphone was positioned in one of the ends to capture the signal produced by impact with the sphere at the other end of the sample. The setup of the experiment is illustrated in Figure 3. Figure 3(a) shows the computer with Soundcard Oscilloscope software.The impact locations with the sphere and the capture of acoustic signals on the glass samples can be seen in the top view shown in Figure 3(b).

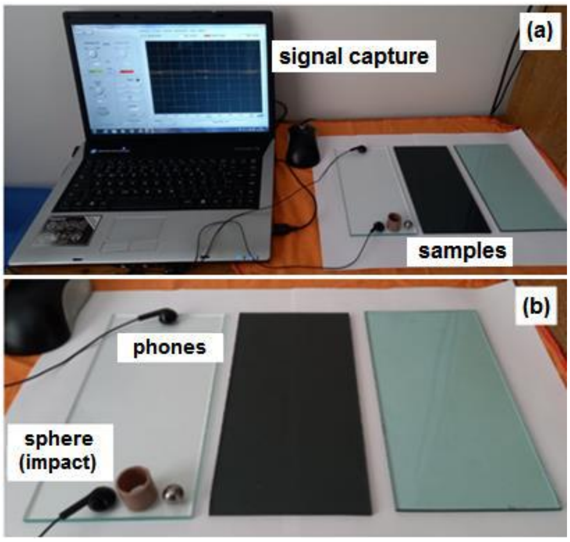


Fig.3: Acoustic waves testing: (a) system used for signal capture, (b) measurement procedure

Figure 4 shows an acoustic wave signal captured and displayed on the computer screen. In this experiment, the type of phone used as a signal receiver is not sensitive enough to capture external noise or vibrations that could be transmitted to the digital oscilloscope and interfere with the measurements. This fact can be evidenced by the red line presented just below the acoustic signal in Figure 4. The red line represents the signal before the measurements, while the green line represents the acoustic signal after the impact. Thus, there is no external noise or vibrations before the measurements.

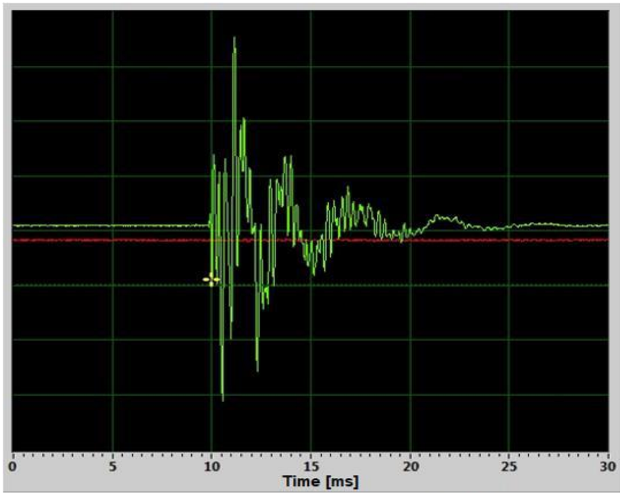


Fig.4: Example of the acoustic signal captured on the glass surface

The acoustic signals were also analyzed as a function of the vibration frequency. For this, Fast Fourier Transform (FFT) method was used, that is widely used in the study of signal processing and several other applications in physics and engineering. This procedure was performed to observe the excited frequencies in the glass samples during the propagation of the acoustic wave.

III. RESULTS AND DISCUSSION

Theresults obtained with the propagation of acoustic waves on the glasses surface are shown in Figure 5.In Figures 5(a), (c) and (e) are shown the overlapping acoustic signals, resulting from 20 measurements, as well as the average acoustic signal. Analyzing the results, it is possible to observe that all measurements were reproducible in each of the investigated glasses with only a small variation in the amplitude.

Small variations in the amplitude occurs due to procedure adopted for the abandonment of the steel sphere in free fall. Even using a PVC pipe as an artifice to maintain a constant height millimeter changes in free fall height may occur. The averageacoustic signal for the colorless, smoked and green glasses are shown in Figures 5(b), (d) and (f). Analyzing the results, it can be seen that the amplitude of the acoustic signal decreases from colorless glass to smoked and from smoked to green. This fact can be verified by analyzing the values on the vertical axes of amplitudes in the figures.

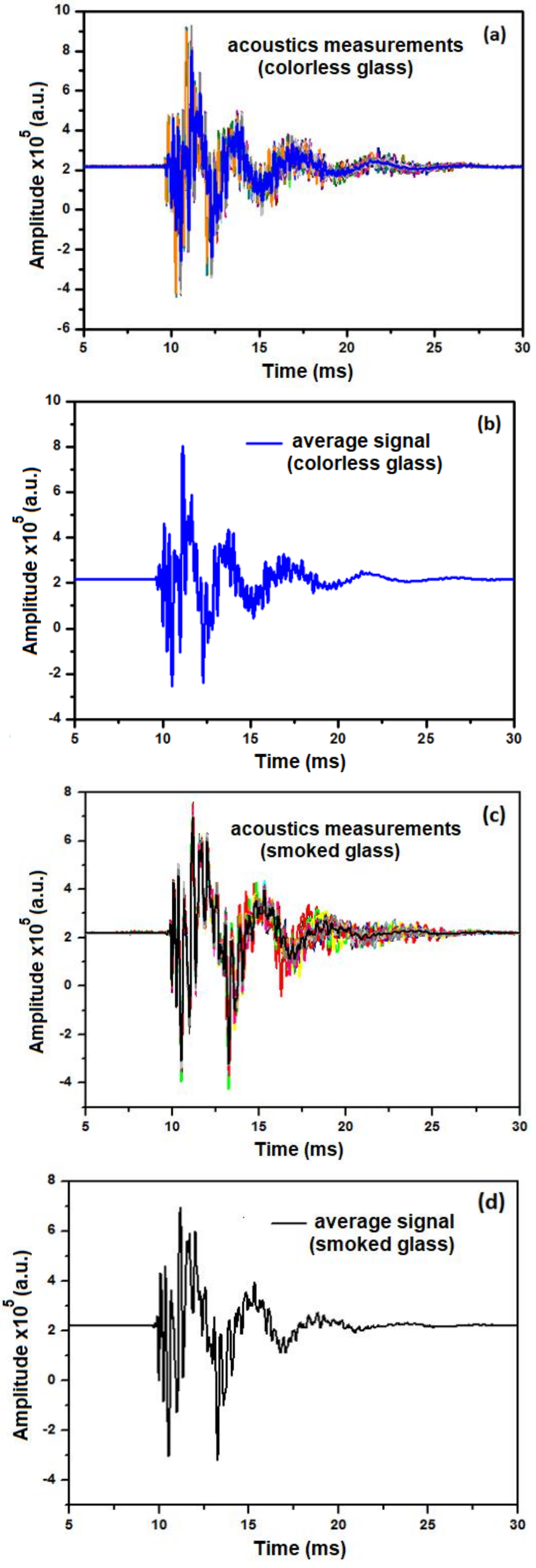
In general, the behavior of the signals obtained on the glass samplesis similarand the largest amplitudes are observed in the region situated on the time axis between 9.78 *ms* and 12.5 *ms*. In the region above 12.5 *ms*, the signals of acoustic waves are attenuated and the decay of the amplitudes is observed. To verify this behavior more clearly, the average acoustic signals were overlapping and shifted along the vertical axis of the amplitudes (Figure6). After that, the region on the time axis between 9.78 *ms* and 12.5 *ms* was enlarged for comparative purposes (Figure 7).

From the enlargementof the signal obtained in the colorless glass, it was found that the investigated region of the acoustic wave consists of 10 amplitude peaks identified on the time axis. These peaks were namedfrom P1 to P10 and are shown in Figure 7(a). In the result, it is still possible to observe a tendency of overlapping between P3 and P4, and also between peaks P6 and P7.

In the enlargement of the signal obtained for the smoked glass, it was found that the investigated region consists of only 7 amplitude peaks, as shown in Figure 7(b). The P1, P2, P4 and P5 peaks are located in the same positions as P1, P2, P5 and P7peaks, present in the signal obtained for the colorlessglass. Furthermore, P3 in the smoked glass signal resembles a complete overlappingbetween P3 and P4 shown in the colorless glass signal. This behavior also occurs in P5, which corresponds to the complete overlappingbetween P6 and P7 peaks observed in the colorless glass signal. The overlapping of peaks in the smoked glass signal reduces the number of visible peaks in the investigated region and favors the appearance of wider peaks, when compared to the peaks present in the acoustic signal of the colorless glass.

According to Figure 7(c), only P1 is not in overlapping with the other peaks present in the signal measured for the green glass. In addition, P1 is the only peak observed at the same position in all signals obtained on the samples.

In the acoustic signal of the green glass, Figure 7(c), a greater number of overlapping peaks results in wider peaks than those observed on the colorless and smoked glass signals. This indicates that acoustic signal on the green glass is more attenuated than signals observed on the other glass samples shown in Figures 7(a) e 7(b).



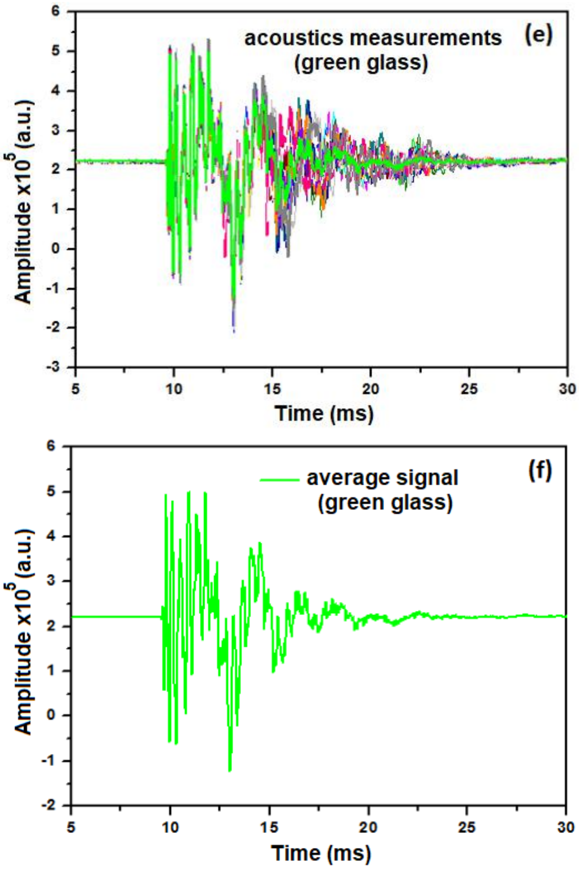


Fig.5: Acoustic signals measured on the glass samples:(a),(c), (e)overlapping acoustic signals; (b), (d), (f)average acoustic signal for each sample

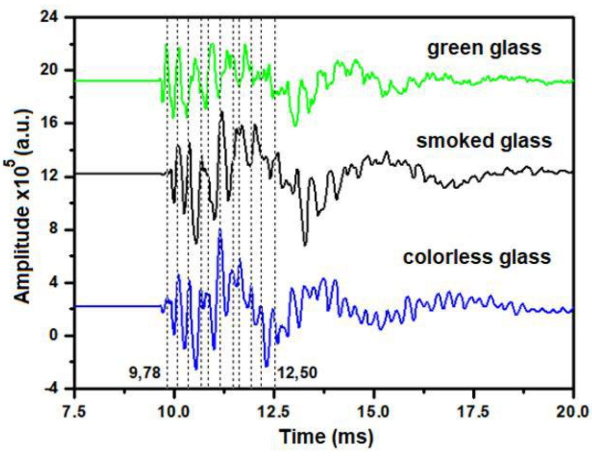


Fig. 6: Overlapping amplitudes of the average acoustic signals

As all investigated samples have practically the same dimensions and surface roughness, an explanation for the attenuation of the signals on the smoked and green glasses could be in their different chemical compositions, which could influence the stiffness values.

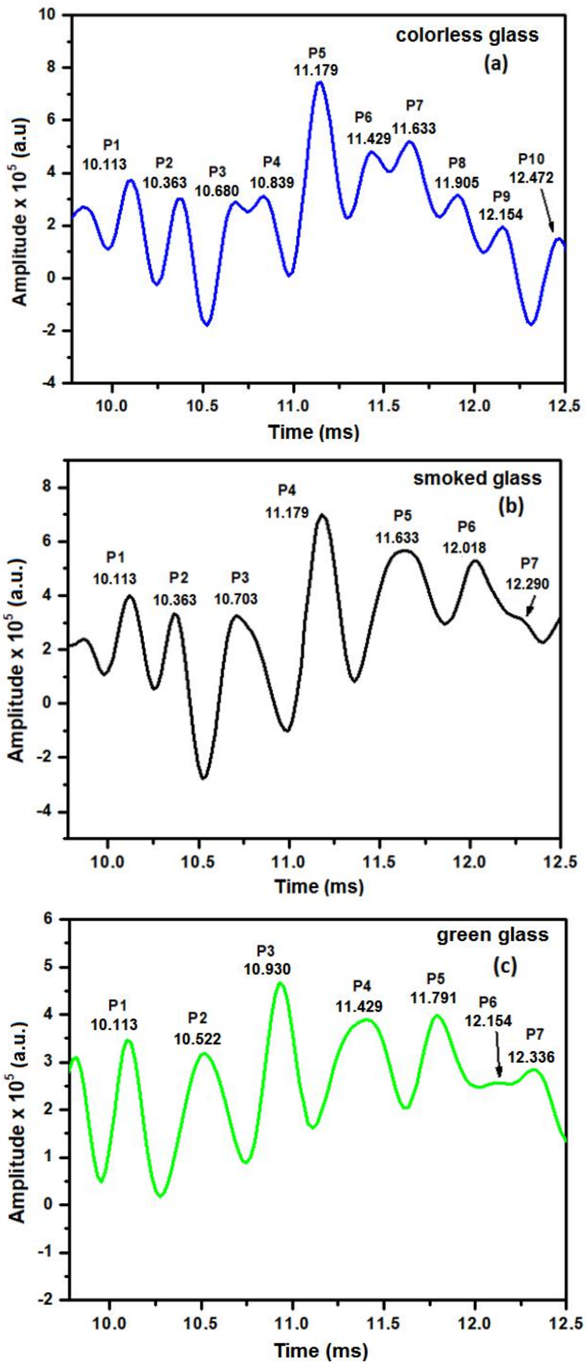


Fig. 7: Enlargement to acoustic signals obtained on the glass samples: (a) colorless, (b) smoked and (c) green

The results obtained for the mechanical properties calculated by Equations 2, 3 and 4 are presented in Table 2.Analyzing the results of V_L and V_S it is noticed that they are smaller for the samples with higher values of *E* and *H*. This behavior was also observed in boron-based glasses, when they are doped with different percentages of zinc oxide (ZnO) or lead oxide (PbO) [19].

In solid materials, the values of*E* are associated with their stiffness. Therefore, colorless glass has less stiffness than smoked glass, which in turn is less stiffness than green glass. These results also agree with the microhardness *H*, whose values are higher in the more stiffness glasses. In soda-calcium glass, the values of Poisson´s ratio are between 0.20 and 0.22. Thus, the results obtained for $\nu = 0.22$ shown in Table 2 were expected [6].

The values found for the *E* and *H* can explain the attenuation and the overlapping peaks presents in acoustic signals of glass samples. For example, in the colorless glass (E = 49.01 GPa and H = 3.75 GPa) the effects of attenuation and overlapping peakswere smaller than those observed in the green glass signal (E = 51.06 GPa and H = 3.91 GPa). Therefore, the results suggest that the attenuation of acoustic signals is influenced by the increase in stiffness and microhardness of the glasses.

In order, to analyze the acoustic signals without the effects of overlapping peaks, the average signals in Figure 6 were investigated as a function of vibration frequency. For this purpose, the Fast Fourier Transform method was used. Figure 8 shows the signalobtained as a function of frequency for glass samples, where each amplitude peak represents an excitation frequency resulting from the impact of the steel sphere on the samples surfaces.

In colorless glass, whose acoustic signal is shown in Figure 8(a), 05 characteristic peaks were identified, being three of them located between 0.0020*Hz* and 0.0050*Hz*frequency. The other two peaks were identified between 0.0060*Hz* and 0.0100*Hz*frequency. Some peaks of smaller amplitude can be observed above of0.0100 Hz. However, these peaks are located at the region of greater attenuation on the acoustic signaland were discarded from the following steps of analysis of the results.

Figures 8(b) and 8(c) show the acoustic signals for the smoked and green glass, respectively. These results also present a behavior similar to that reported for colorless glass. However, in the green glass, 04 characteristic peaks were found between 0.0020 Hz and 0.0050 Hz. Although the acoustic signals for smoked and green glasses are similar to the signal of the colorless glass, comparing the amplitude peaks it is noticed that these are shifted to lower frequencies. To more clearly analyze the displacement of the signals, the location values peaks on the frequency axis are in Table 3.

The appearance of a peak in the signal of green glass, whose presence is not observed in the colorless and smoked glass, was disregarded for the comparative analysis of the peaks and their respective frequency values.

Table. 2:Properties calculated for the glass samples

Glass	ρ (kg/m^3)	V_L (m/s)	V_T (m/s)	*E* (GPa)	*v*	*H* (GPa)
Colorless	2489.18	4736.84	2842.10	49.01	0.22	3.75
Smoked	2660.76	4639.18	2783.51	50.25	0.22	3.84
Green	2759.90	4591.84	2755.10	51.06	0.22	3.91

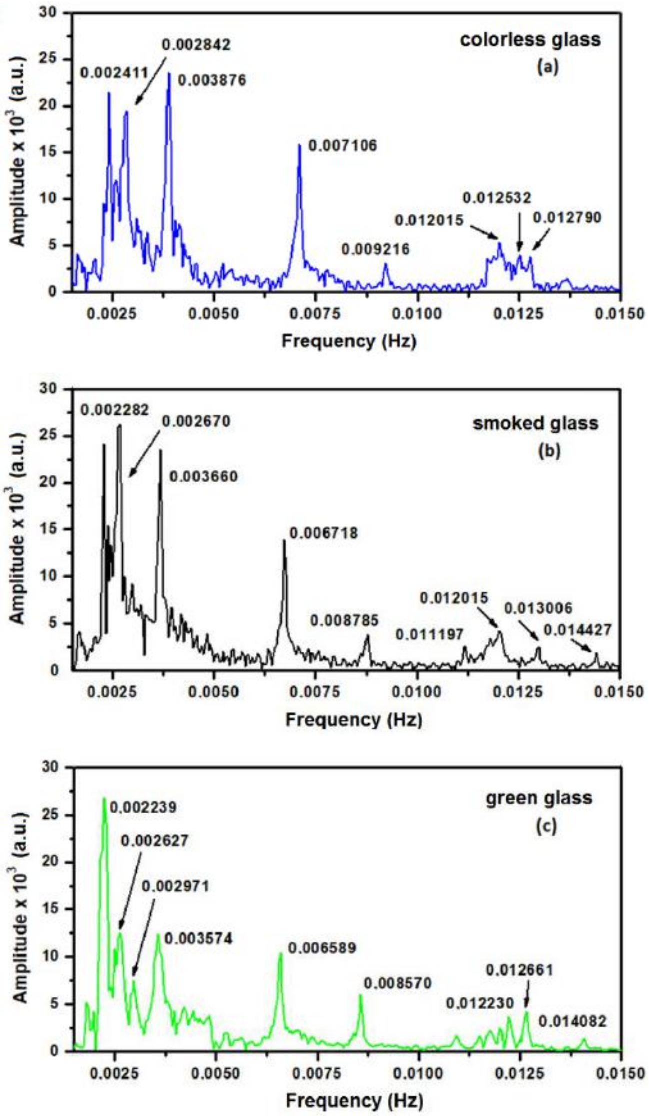


Fig.8: Acoustic signal as a function of frequency

It is believed that the appearance of a new peak observed in the signal of green glass may be associated with an intrinsic characteristic of the chemical composition of the sample. Colorless and smoked glass have similar chemical compositions, different only in the highest percentage of Fe_2O_3 present in smoked glass [4, 6, 7]. This fact may explain why the signals of colorless and smoked glass are similar in the number of amplitude peaks on the non-attenuated region. Therefore, the appearance of a new peak at 0.002971 Hz frequency in the green glass signal may be associated with the presence of chemical elementssuch as CeO_2, TiO_2 or Cr_2O_3, commonly observed in this type of glass.

Table. 3: Amplitude peaks on the frequency axis

	Frequency (Hz)		
Peaks	**Colorless**	**Smoked**	**Green**
1	0.002411	0.002282	0.002239
2	0.002842	0.002670	0.002627
3	0.003876	0.003660	0.003574
4	0.007106	0.006718	0.006589
5	0.009216	0.008785	0.008570
***H* (GPa)**	**3.75**	**3.84**	**3.91**
***E* (GPa)**	**49.01**	**50.25**	**51.06**

It is important to emphasize that this hypothesis was based on reports found in the literature on the general chemical composition of colorless, smoked and green glass, but it will only be proved with a chemical analysis of the samples.

Similar to what was observed for the acoustic signals as a function of time, the signals as a function frequency seem to be related to the stiffness and microhardness of the glass samples. It is believed that, in the more stiffness glass (green glass), characteristic peaks arise at lower frequencies due to the greater attenuation in the propagation of acoustic waves, as discussed earlier. Therefore, from the results presented in Table 3 it is possible to associate the frequency peaks with some mechanical characteristics of the samples as Young's modulus (*E*) and microhardness (*H*).

IV. CONCLUSION

In this study, it was possible to verify in glass samples that the attenuation of acoustic signals is associated with higher values of Young's modulus and microhardness. The signals with higher attenuation showed characteristic peaks at lower frequencies, suggesting a possibility to identify and characterize some mechanical properties of soda-lime glass by means of acoustic signal analysis.

Although the glass samples presented different of density and ultrasonic velocities values, the calculated value for the Poisson's ratio was the same for all glasses. This result is in agreement with what was expected for soda-lime glasses and reinforces the use of ultrasonic waves for a reliable estimate of the Young's modulus and microhardness in the glassesused in civil building.

The results were obtained with a rapid method that attests to the possibility of using acoustic signals as a non-destructive technique for characterizing the mechanical properties of soda-lime glasses. In the future studies, acoustic signals will be also used to investigate other properties such as compressibility and shear modulus.

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