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The Effects of Boric Acid on Fiberboard Properties Made from Wood/Secondary Fiber Mixtures: Part 4. Insulation Properties of Boards

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Authors' contributions

This work was carried out in collaboration between both authors. Authors AIK and HTS designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors AIK and HTS managed the analyses of the study. Author AIK managed the literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

The boards made from wood and secondary fibers appear to be well correlated secondary fiber/wood fiber proportions in terms of the behavior of the sound acoustic properties. However, boards were generally shown better acoustic (sound absorption) properties in high frequencies. Moreover, at middle level frequencies and lower boric acid addition (5.0%), the boards made from equal proportion of wood and secondary Old Corrugated Containers (OCC) and newspaper fibers shows markedly improved acoustic properties.
However, the boric acid addition had only marginal effects on relative thermal resistance values either improve or increase thermal properties, vice versa. It was observed that both the secondary

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fiber ratio contributes to the control of the relative thermal resistance values, and that under certain experimental conditions thermal resistance value of as low as 0.140 W/mK can be achieved.
It was also found that increasing boric acid content positively impacts on the boards degradation that decomposition temperature was increased for boards in all boric acid conditions. This is an important result considering boric acid affects improving board's thermal resistance some level. Moreover, the endothermic peaks at 71°C, 266°C and 333°C for Differential Scanning Calorimetry (DSC) have clearly consisted with Thermogravimetric Analysis (TGA) curves.

Keywords: Waste paper; secondary fibers; recycling; acoustic properties; thermal insulation.

1. INTRODUCTION

The growing awareness of health towards the environmental implications associated with building materials has increased the attention towards natural materials. However, the natural fibers have often been reported to have good insulation properties, have no harmful effects on health, and are available in large quantities often as a waste product of other production cycles [1]. In recent years, natural fibers which are considered as environmentally friendly materials have been considered raw materials for producing insulation panels (i.e. sound or heat) at a reduced cost. For that reason, those materials are becoming an important alternative to traditional synthetic ones for building applications [2]. A number of researchers have already reported that panel products from secondary fibers exhibit appropriate properties, often more advantageous than synthetic fibers [2-6].

Based on their microscopic configurations, porous absorbing materials have been classified as cellular, fibrous, and granular [7]. The fibrous materials generally include a series of tunnel like openings that are formed by interstices in material fibers. However, pores that a continuous channel of communication with the external surface of the material called "open pores" allow sound absorption properties some level [7]. It is well established that in order to absorb sound, materials should have high porosity to allow the sound entering their matrix, and facilitate its dissipation. Nevertheless, there is still little knowledge about the sound absorption behavior of cellulosics especially secondary fibers from various sources.

On the other hand, thermal insulation has become important issue for housing and building constructions worldwide. Therefore, numerous insulation products have been already developed with technological advances. The legislations have acted as the basic requirements under the building constructions in many countries. These products vary in terms of color, surface finish and texture, core composition and, most importantly, performance. Moreover, cellulose based products have already reported to be good insulation products in building applications [7-10]. Yet the market is still dominated by synthetic insulating materials. It has already well established that cellulosic fibers are defined as high wettability and absorbability as an open pore structures. Due to their special structure, the cellulose based materials need to be protected/modified against abiotic and biotic biological attacks (e.g. against fungi, sun, rain, heat, etc.,) [11]. Nevertheless, the negative properties of cellulosic materials may be largely modified by chemical treatments.

An understanding of the phenomena of noise, materials used for its suppression, and the characterization of those materials for predict their acoustic performance is necessary while successfully developing materials for acoustic absorption applications [10]. Following literature reviews of previous studies about the insulation properties of some natural materials, it was considered that the porous structure of low or medium density cellulosic composites might give advantage for insulation purposes.

The secondary fibers are typically shorter and stiffer (rigid) than the original fibers. However, as a result of recycling process, the fibers are undergoing various modifications. Some of the important modifications are; length of fibers has shortened, surface areas narrowed, and the bonding potentials decreased. Theoretically, it is known that long fibers have higher strength, surface area and bonding properties than short fibers. Those clearly influenced swelling/plasticizing and hydrogen bonding potential of fibers. Thereby, the mixture of wood fiber and secondary fiber is used to improve strength properties of boards and evaluate effects of secondary fiber content in furnish.

The systematic approaches have carried on different waste paper substrate to determine clear effects on recycling approach and chosen methods. In the former parts of this study, ‘The Effects of Boric Acid on Fiberboard Properties Made from Wood/Secondary Fiber Mixtures: Part 1. Utilization of Recycled Newsprint Paper Fibers’; ‘The Effects of Boric Acid on Fiberboard Made from Wood/Secondary Fiber Mixtures: Part 2. Utilization of Recycled Old Corrugated Container Fibers’; and ‘The Effects of Boric Acid on Fiberboard Made from Wood/Secondary Fiber Mixtures: Part 3. Utilization of Recycled Waste Office Paper Fibers’ have already been published in other journals. However, this study aimed to study more fundamental understanding for the acoustic and thermal performance of cellulosic composites that were produced from recovered secondary fibers in a manner that may help materials researchers new to this area gain the understanding and skills necessary to make meaningful contributions to this field of study.

2. MATERIALS AND METHODS

The post-consumer waste papers (office and newspaper) and old corrugated container products (OCC) were obtained from local waste paper trader, Isparta, Turkey. The boric acid was supplied directly from Etibor A.Ş, as laboratory purity, Bandırma-Turkey.

The waste papers were carefully sorted according to their inherent properties. That are; office papers coded as A; newspapers coded as B; and OCC coded as C. These waste materials separately were converted to pulp using a 5 L. capacity, laboratory type standard disintegrator in water.

The first step of this study was to prepare boards from recycled secondary fibers individually in order to determine the suitability of these waste materials for insulation purposes. The second step was to determine the effects of secondary fiber proportions (A/B/C) in wood fiber (W) and boric acid addition (BA,%) on the performance of the boards. Table 1 presents the boards codes that proportion of secondary/wood fiber ratios and boric acid content in furnish. The detailed information on panel production conditions, recycling process and experimental procedures have already reported in former publications [12-14].

Thermogravimetric Analysis (TGA) is carried out using a Perkin Elmer SII instrument, for measuring changes in properties of boards as a function of increasing temperature (with constant heating rate). In TGA, the mass (weight) of specimen is monitored continuously as the ambient temperature reaching to 1200°C. During these heating, the graph drawn by the mass lost against the temperature is called "thermogram". This thermogram is used for qualitative and quantitative analyses of samples. The thermogravimetric analyzer has a precision analytical technique and provided with furnace, temperature controller, computer based program and a recorder. The recorder save data and drawn graphs of the sample mass modification against the temperature. It has conducted in an inert gas atmosphere. In TGA technique, purity, degradation behavior under various temperature and chemical kinetics of sample are examined.

Differential Scanning Calorimetry (DSC) Thermal Analysis is widely used to measure the amount of energy absorbed by a sample when it is heated, providing quantitative and qualitative data on endothermic (heat absorption) and exothermic (heat evolution) processes. Hence, the thermal properties of boards were evaluated by the use a Perkin Elmer 8000 DSC instrument. The small amount of sample (1-2 gr) mg. is placed in a suitable pan and sits upon a constantan disc on a platform in the DSC cell with a chromel wafer immediately underneath. Temperature can range from -180°C to 725°C, though an inert atmosphere is required above 600°C.

The sound absorption properties (Acoustic) of boards were determined according to TS EN 10534-2 standard that at least 12 samples tested with Brüel&Kjaer Tube Type 7758 instrument. With microphones in a pod, 125, 250, 500, 1000, 2000, 4000, 5000, 6300 Hz in the frequency range [15]. In this method, a large tube is used for measuring low-frequency sound absorptions (between 50 Hz and 1.6 kHz). In this sense, samples with a diameter of 100 mm are prepared for large tube measurements. However, a small tube is useful for measuring sound absorption coefficient in the 1.6 kHz to 6.4 kHz frequency range. Hence, samples with a diameter of 29 mm are prepared to make measurements in a small tube as well [15]. In based on the impedance method, the sound absorption coefficient ($\propto$) is expressed by the following formula (1, 2) [16,17].

$$\propto = 1 - |R|^2 \quad (1)$$

$$R = \frac{Z_S - \rho_0 c}{Z_S + \rho_0 c} \quad (2)$$

Where, R: sound pressure reflectance coefficient, Zs: surface impedance (Pa s/m), P_0: characteristic impedance (Pa s/m), c: sound velocity (m/s).

While many combinations were utilized during recycling procedure of cellulose fibers, some code number and abbreviations were established throughout the study given in Figures and Tables. These are: a: 5.0%, b: 10% boric acid content, weight/weight; W: Wood fiber, S: Secondary fiber A: Secondary office fiber, B: Secondary newspaper fiber, C: Secondary Old Corrugated Container fiber; 1, 2, 3, 4, and 5: recycling number.

3. RESULTS AND DISCUSSION

The behavior of the sound acoustic properties of boards made from wood (W) and secondary fibers (A/B/C) are shown in Table 2. It can realize that the sound absorption properties of boards were generally better in high frequencies. This is important for considering board's sound absorption coefficient influenced by frequencies. In this regard, these materials could be utilized in specific sound or frequency level as sound barrier materials.

When the sound absorption coefficient was measured by the impedance tube method, even thin samples (10 mm) utilized, it was observed that the board's sound coefficients have increased at the 1000-2000 Hz impedance range. It is important to note that peak sound absorption coefficient increase at 0.81 levels of the boards made from secondary OCC fibers at 2000 Hz range. Similarly, boards made from secondary office fibers and newspaper fibers were shown 0.60 and 0.56 sound absorption coefficient, respectively at same impedance range (2000 Hz). It looks like there is a positive correlation between frequency and sound absorption properties. It could be concluded that it is possible to use boards made from secondary paper fibers as a sound absorbent material in the constructions with specific range.

In order to examine the effect of fiber type and boric acid content at various frequencies, the sound properties of boards are shown in Figs. 1-3. The sound absorption of board appears to be well correlated secondary fiber/wood fiber proportions. However, the sound absorption values of boards made from office secondary fiber/wood (Fig. 1) show a sound damping that it was steady increase up to 3000 Hz and then decreasing. Interestingly, boards made from mixture of secondary newspaper and OCC fibers with wood shows more less similar shape (Figs. 2-3). It is clear that at middle level frequencies and lower boric acid addition (5.0%), the boards made from equal proportion of wood and secondary OCC and newspaper fibers show markedly improved sound barrier properties. It was also realized that the sound absorption shows a various level of increase and decrease with some variables but in high frequencies it shows sudden increase in all conditions. It may be suggested that at middle level noise frequencies, the boards made from equal proportion of wood and secondary newspaper (Fig. 1) and OCC shows (Fig. 3) markedly improved sound properties some level. The presented data clearly show that the sound frequencies, fiber mixture proportions and non-fibrous content in furnish (boric acid) influenced board's sound absorption properties. Moreover, these comparisons between the boards and the measured results reveal that the secondary fibers response of a board with initial sound properties similar to wood (Table 2) up to 4000 Hz and beyond this level, the sound absorption markedly decreased (Figs. 1-3).

Table 1. The board's code numbers and wood and secondary fiber (W/S) ratio with boric acid (BA) content

Board Bodes	(W/S) (%)	BA (%)	Board Bodes	(W/S) (%)	BA (%)
A0-B0-C0	100:0	0.0	**A0-B0-C0**	100:0	0.0
A0a-B0a-C0a	100:0	5.0	**A0b-B0b-C0b**	100:0	10.0
A1a-B1a-C1a	75:25	5.0	**A1b-B1b-C1b**	75:25	10.0
A2a-B2a-C2a	50:50	5.0	**A2b-B2b-C2b**	50:50	10.0
A3a-B3a-C3a	25:75	5.0	**A3b-B3b-C3b**	25:75	10.0
A4a-B4a-C4a	0:100	5.0	**A4b-B4b-C4b**	0:100	10.0

Table 2. Sound absorption coefficients of boards made from secondary office fiber/wood fiber mixtures at various frequencies

Samples	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	5000 Hz	6300 Hz
A0a	0.062	0.08	0.11	0.28	0.6	0.40	0.38	0.41
A1a	0.062	0.055	0.058	0.212	0.352	0.212	0.38	0.18
A2a	0.025	0.056	0.05	0.15	0.27	0.1	0.28	0.11
A3a	0.032	0.043	0.05	0.18	0.48	0.19	0.42	0.2
A4a	0.026	0.043	0.11	0.23	0.1	0.22	0.22	0.11
A0b	0.04	0.08	0.11	0.28	0.60	0.40	0.38	0.41
A1b	0.04	0.09	0.15	0.33	0.44	0.41	0.38	0.39
A2b	0.05	0.09	0.10	0.24	0.34	0.27	0.28	0.25
A3b	0.05	0.07	0.10	0.28	0.60	0.47	0.42	0.44
A4b	0.04	0.07	0.15	0.18	0.29	0.22	0.22	0.25
B0a	0.025	0.05	0.06	0.18	0.48	0.16	0.38	0.19
B1a	0.032	0.05	0.05	0.16	0.44	0.18	0.44	0.22
B2a	0.038	0.06	0.11	0.16	0.14	0.06	0.18	0.2
B3a	0.01	0.03	0.04	0.9	0.05	0.03	0.09	0.38
B4a	0.03	0.03	0.07	0.18	0.42	0.14	0.27	0.1
B0b	0.04	0.08	0.11	0.28	0.6	0.4	0.38	0.41
B1b	0.08	0.09	0.09	0.25	0.56	0.47	0.44	0.47
B2b	0.06	0.11	0.2	0.25	0.17	0.16	0.18	0.42
B3b	0.02	0.04	0.06	0.13	0.07	0.09	0.09	0.08
B4b	0.04	0.06	0.11	0.28	0.53	0.37	0.27	0.22
C0a	0.02	0.05	0.06	0.18	0.48	0.16	0.38	0.19
C1a	0.02	0.04	0.05	0.15	0.64	0.12	0.33	0.17
C2a	0.02	0.06	0.08	0.1	0.12	0.1	0.56	0.09
C3a	0.02	0.03	0.04	0.09	0.2	0.22	0.33	0.13
C4a	0.02	0.03	0.04	0.09	0.13	0.08	0.25	0.11
C0b	0.03	0.08	0.11	0.28	0.6	0.4	0.38	0.41
C1b	0.03	0.07	0.09	0.24	0.81	0.32	0.33	0.37
C2b	0.04	0.1	0.15	0.19	0.13	0.14	0.2	0.19
C3b	0.04	0.056	0.08	0.15	0.25	0.55	0.33	0.29
C4b	0.04	0.05	0.07	0.15	0.17	0.22	0.25	0.23

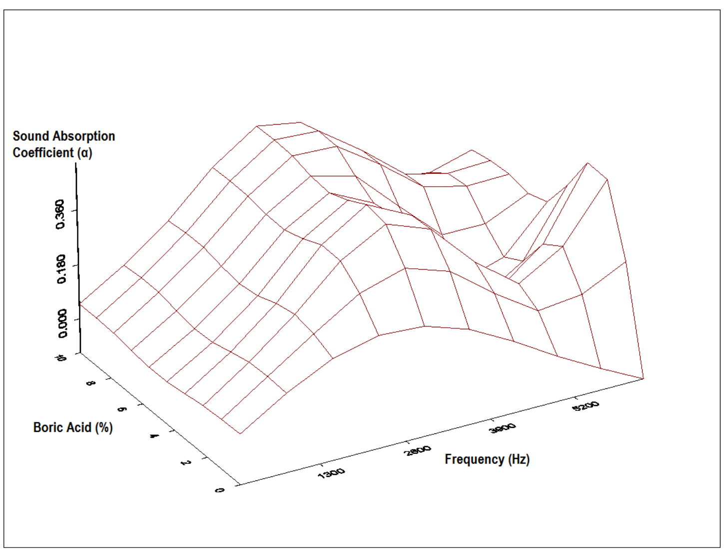

Fig. 1. The effects of office paper mixtures with wood fibers (1:1) on sound absorption properties

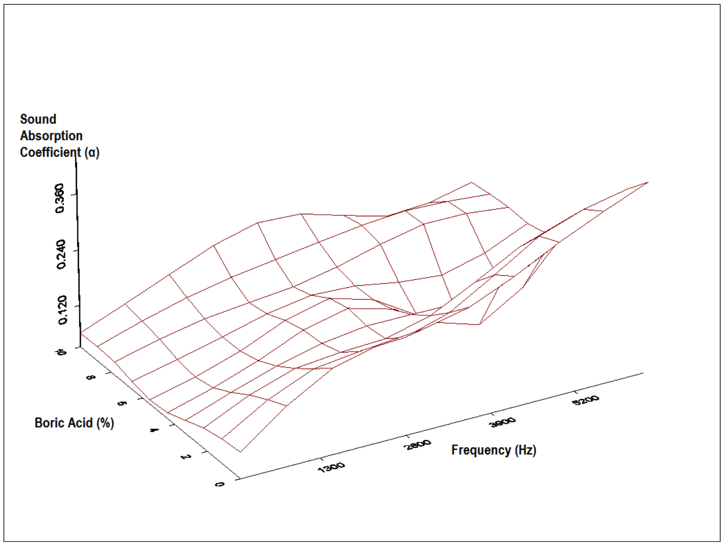

Fig. 2. The effects of newspaper mixtures with wood fibers (1:1) on sound absorption properties

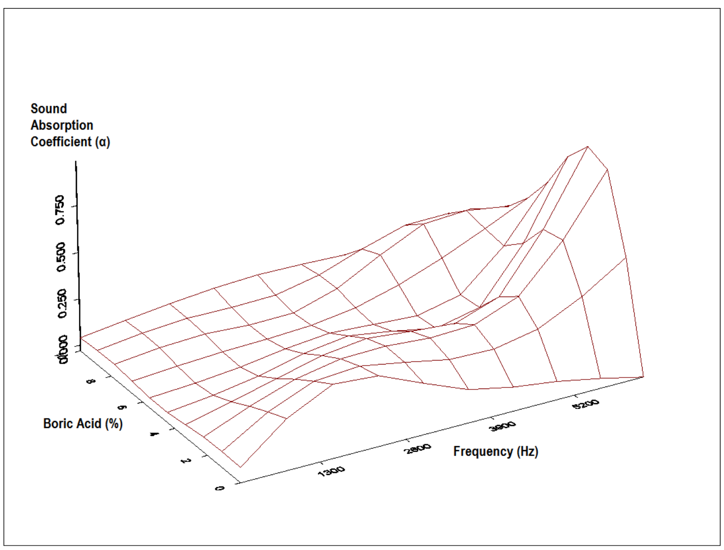

Fig. 3. The effects of OCC mixtures with wood fibers (1:1) on sound absorption properties

Table 3 shows thermal resistance properties of boards. It has realized that for boards made from only secondary newspaper and office paper fiber the thermal values of 0.158 (A4) and 0.162 W/mK (B4) are lower than boards made from only wood fibers (A0, B0 and C0). According to thermal measurements, the boric acid addition had only marginally effects on relative thermal resistance values either improve or increase thermal properties, vice versa. However, one may be concluded that both the secondary fiber ratio contributes to the control of the relative thermal resistance values, and that under certain experimental conditions thermal resistance value of as low as 0.140 W/mK (C3a) could be achieved (Table 3).

The pictures of flame combustion test's results are shown in Fig. 4. It can be clearly seen that all the boards manufactured with secondary fibers and boric acid are shown to pass the minimum level of B2 class that shows only slight tendency to char on surface (not reaching the 150 mm level). These comparison between the board fiber types and proportions with boric acid content and the measured results reveals that these boards may be classified as A2S1 class material according to standard TS EN 13501-1 [18,19].

A typical TGA and DSC diagrams for boards made from secondary newspaper's fibers (B) are shown in Figs. 5 and 6, respectively. It can be realized that increasing boric acid content has positive impact on thermal degradation that decomposition temperature was increased in all boric acid (5.0-10%) addition conditions (Fig. 5), compare to boards that made without boric acid (0%). This is an important result considering boric acid affects improving board's thermal resistance. However, this might be expected considering a number of literature findings on composites containing boric acid's thermal resistance properties. In TGA micrographs, regions were determined for the approximate starting and ending points of the TGA curve, which shows the breakdown of the organic matter and volatiles [20]. Initially, up to 100°C, 7-10% mass loss occurs due to vaporization of moisture in the material. However, at the range of 110-220°C, the mass remains approximately constant, with no water remaining in the cell wall. After this point, the organic matters started to warm up and two disruptions occurred. There is progressive increase of mass lost between 300-360°C and total mass of sample reached to 75-80%. Increasing temperature from 400 to 900°C, the passage to the gas flow is accelerated and the cell wall is degraded by the internal pressure. This is occurring at lower slope than the other temperatures and the mass loss reached to 90%. At this level (900°C) the evaporation of cell wall constituents has completed and pure carbon remains. It is important to note that the endothermic peaks at 71°C, 266°C and 333°C for DSC (Fig. 6) have clearly consisted with TGA curves.

The thermal behaviors of boards were determined in TGA. A detailed examination of DSC curves, the peak formation was observed at 3 points. The highest deleterious effects on boards structure was observed at 300°C that inorganic and thermoset structures are degraded. The second peak start at 380°C and continued to 410°C while the highest at 390°C. The third peak was observed at up to 650°C and this is considered to be boric acid degradation level.

The summary data of TGA analyses are shown in Table 4. It could be seen that increasing boric acid has positive impact on thermal degradation that decomposition temperature was increased for all boards manufactured with secondary fiber and boric acid content. This is clear effects for improving degradation against thermal of boards made with boric acid.

Table 3. Thermal insulation properties of boards made from wood and secondary fiber mixtures

Samples	W/mK	Samples	W/mK	Samples	W/mK
			Office paper's fibers		
A0-B0-C0	0.175	**A0a**	0.176	**A0b**	0.177
A1	0.172	**A1a**	0.183	**A1b**	0.195
A2	0.170	**A2a**	0.176	**A2b**	0.175
A3	0.173	**A3a**	0.181	**A3b**	0.246
A4	0.158	**A4a**	0.177	**A4b**	0.197
			Newspaper's fibers		
A0-B0-C0	0.175	**B0a**	0.168	**B0b**	0.186
B1	0.149	**B1a**	0.154	**B1b**	0.217
B2	0.141	**B2a**	0.149	**B2b**	0.224
B3	0.182	**B3a**	0.194	**B3b**	0.197
B4	0.162	**B4a**	0.198	**B4b**	0.211
			OCC's fibers		
A0-B0-C0	0.175	**C0a**	0.180	**C0b**	0.240
C1	0.180	**C1a**	0.190	**C1b**	0.200
C2	0.160	**C2a**	0.170	**C2b**	0.190
C3	0.180	**C3a**	0.140	**C3b**	0.220
C4	0.200	**C4a**	0.220	**C4b**	0.210

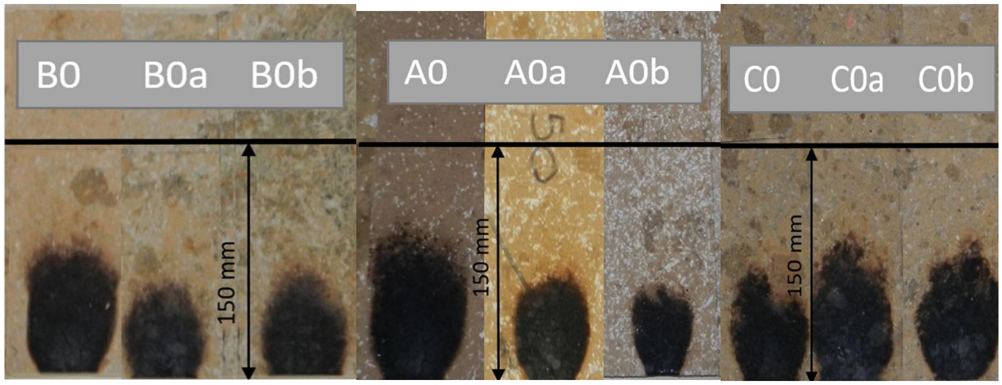

Fig. 4. The pictures of flame combustion test's results

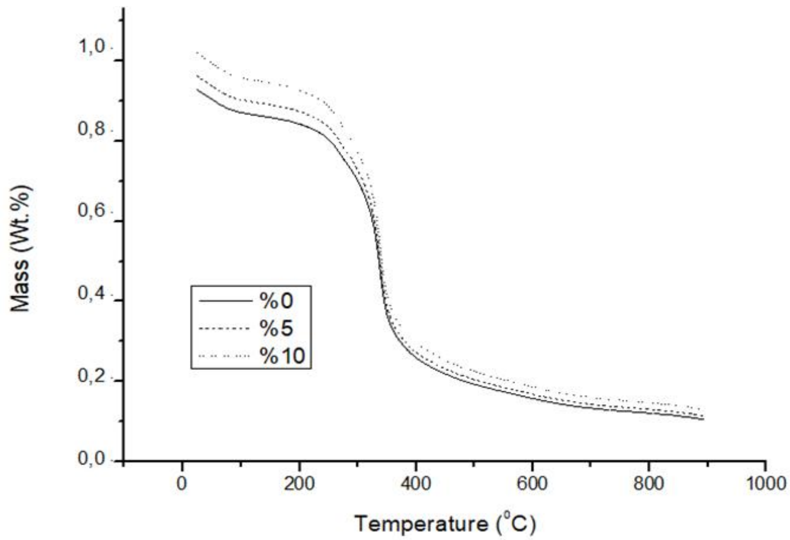

Fig. 5. Typical TGA diagrams for boards made from secondary newspaper's fibers

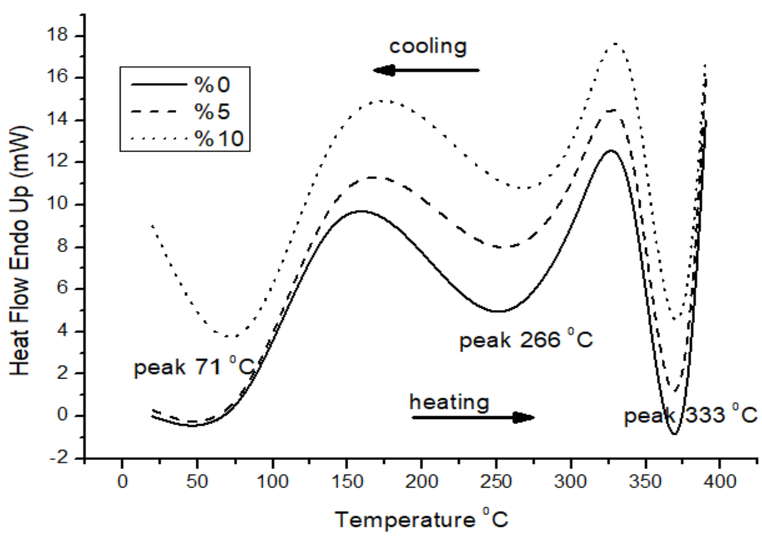

Fig. 6. Typical DSC diagrams for boards made from secondary newspaper's fibers

Table 4. TGA analyses of boards (Tb: initial temp, Tm: max. temp, Ts: Final temp.)

Board code	Tb	Tm	Ts	Board code	Tb	Tm	Ts	Board code	Tb	Tm	Ts
					Office paper's fibers						
A0	252.2	304.2	399.9	**A0a**	255.5	308.1	404.0	**A0b**	260.1	320.2	410.0
A1	255.4	308.9	402.4	**A1a**	266.5	315.2	410.2	**A1b**	261.5	325.5	412.3
A2	266.1	312.5	404.5	**A2a**	263.3	313.3	409.2	**A2b**	265.5	325.2	418.6
A3	265.8	322.9	414.3	**A3a**	270.1	321.9	480.9	**A3b**	270.9	338.5	419.8
A4	275.9	318.5	409.2	**A4a**	272.1	317.1	412.3	**A4b**	269.5	339.5	412.5
					Newspaper's fibers						
B0	252.2	304.2	399.9	**B0a**	255.5	308.1	404.0	**B0b**	260.1	320.2	410.0
B1	253.4	306.1	400.1	**B1a**	261.9	312.4	405.2	**B1b**	263.5	322.5	410.5
B2	260.3	309.3	403.5	**B2a**	263.4	313.3	405.7	**B2b**	263.4	324.4	410.9
B3	260.5	311.2	403.8	**B3a**	264.8	314.6	406.8	**B3b**	264.6	664.5	412.4
B4	261.6	312.9	405.1	**B4a**	265.6	314.7	407.3	**B4b**	265.9	339.3	413.3
					OCC's fibers						
C0	252.2	304.2	399.9	**C0a**	255.5	308.1	404.0	**C0b**	260.1	320.2	410.0
C1	261.5	322.1	418.6	**C1a**	273.1	318.1	412.6	**C1b**	269.3	328.1	419.2
C2	268.2	319.1	406.2	**C2a**	269.2	319.2	410.1	**C2b**	268.2	330.1	426.1
C3	275.1	325.4	420.1	**C3a**	280.1	330.1	416.2	**C3b**	278.3	341.2	421.2
C4	280.2	321.5	410.3	**C4a**	280.6	319.2	419.2	**C4b**	271.2	341.5	419.5

The results presented in Table 4 show the samples had different decomposition temperatures. It can be realized that thermal stability of boric acid treated samples increased as compared to control samples (A0, B0, C0). However, this increasing for 10% BA addition is higher than 5.0% BA added panels. As a result, there were some differences between samples treated with BA in different concentration. It was also found that the changes in TGA curves for samples were somewhat similar shape, but there was usually less weight loss of 10% BA treated samples.

4. CONCLUSION

The population growth with development of new technological machines and the spread of urban population centers have contributed to the increase of energy usage. However, the control of thermal and acoustic insulation, which is any undesired situations, is becoming important because the energy levels and their adverse effects on people. The secondary fibers are derived from waste papers can be considered a very suitable sound absorption material and with having low environmental impact.

The sound absorption coefficient of the boards produced under laboratory conditions was measured as low as 0.02 at 100 Hz while 0.81 at 2000 Hz range of noise. The sound absorption coefficients were found with these experimental boards is considered to be important in terms of noise barrier properties.

A various construction material's sound absorption coefficients have already given in literature. This value has reported to be 0.10 at 250 Hz, 0.04 at 2000 Hz for 12 mm thick gypsum boards while it was reported to be 0.45 at 250 Hz and 0.80 at 2000 Hz for 50 mm thick glass wool. Similarly, it was reported to be 0.29 at 250 Hz and 0.91 at 2000 Hz for rock wool while it was reported to be 0.30 at 250 Hz and 0.79 at 2000 Hz for 50 mm thick polyurethane panel. With having these literature findings, it is reasonably to suggest that the experimental boards made from secondary waste paper fibers have same sound absorbing properties compare to materials that generally utilized in construction for sound absorbing purposes.

However, as a result of the measurements made on the boards, we could be summarize that the increase the amount of secondary fiber content in furnish usually positively effects in terms of sound barrier properties while boric acid has not shown any improvements of that properties. Thus, fibers from waste paper products could be support and provide functional benefits for sound insulation purposes in buildings.

Moreover, the boards made from secondary cellulosic fibers could be used for some building applications regarding thermal and acoustic insulation purposes. Because, these fibers are competitive materials thanks to their low density, good mechanical properties, easy processing, high quantity availability, low price, and reduced environmental impacts for their production.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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