Article

Effects of Wollastonite on Fire Properties of Particleboard Made from Wood and Chicken Feather Fibers

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Abstract: The present study was carried out primarily to investigate the fire properties of particleboards with 5% and 10% feather content. With regard to the flammability of chicken feathers, separate sets of panels were produced with 10% wollastonite content to determine to what extent it could help mitigate the negative effects of the addition of flammable feathers on the fire properties. It was concluded that the inclusion of 5% of chicken feathers can be considered the optimum level, enough to procure part of the ever-growing needs for new sources of raw material in particleboard manufacturing factories, without sacrificing the important fire properties. Moreover, the addition of 10% wollastonite is recommended to significantly improve the fire properties, making the panels more secure in applications with higher risks of fire. It is further stated that a chicken feather content of 10% is not recommended as it significantly deteriorates all properties (including physical, mechanical, and fire properties).

Keywords: fire-retarding property; particleboard; piloted flame; wollastonite; wood-based composite

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1. Introduction

Wood and wood-based composites are susceptible to abiotical and biological decay by fungi, insects, and fire; therefore, over the years many methods, preservatives, and fire retardants have been used to help mitigate these drawbacks [1–6]. The history of fire retardants goes back to applying inorganic salts many years ago. It was only in the last century that solid wood was pressure-impregnated with fire retardants [7–10]. Based on this, a new set of building codes emerged, known as Fire Retardant Treated (FRT) Lumber. These codes can be applied to both solid wood species and wood-based building materials. Some chemicals used in FRT Lumber increase the threshold temperature at which thermal degradation occurs [11,12]. This process is translated into a reduction in both the amount of char produced during the process of burning as well as the amount of flammable volatiles. There are other newly developed materials that have used the heat-transferring properties of some mineral and metal materials to prevent the accumulation of heat at one spot, and therefore the ignition of wood or wood-based composite panels can be significantly delayed [5,6,9,13]. One of these new fire retardants is sepiolite. It is a natural hydrous mineral with unique properties which has shown to be effective in improving thermal conductivity in oriented-strand lumber production and in the fire retardancy of solid wood [14,15]. Graphene is another newly developed fire retardant; it consists of a one-atom-thick planar sheet, in which carbon atoms are hexagonally arranged, and it is therefore considered a nano-material. These sheets are densely packed in a honeycomb crystal lattice. Graphene has received appreciable attention over the last two decades due to its special structure and exceptional properties [16].

Traditionally, three vital perspectives were taken into consideration for a chemical to be used as a fire retardant: the kind and amount of toxic gases that are produced, the extent to which the mechanical properties are reduced, and its effects on the hygroscopicity [17,18]. Although all of these perspectives have been elaborated over the years, environmental and health concerns have only recently been taken into consideration. In this regard, wollastonite has been proved to cause no health hazards to either humans or wildlife [19,20], it is a silicate material (CaSiO_3) with no chemical pollution, and it does not have any negative effects on mechanical properties as it does not have any acidic chemicals [5,6,13,21]. Its application in wood-based composites is simple, as it can be physically mixed with resin and sprayed on the furnish. There are many wollastonite mines all over the world and, therefore, the cost of production would be economical in regards to the benefits it adds to wood-based composite panels [5,6,13,21]. Other silicate materials that are currently used in wood-based panels industry include:

- (i) Nanoclays(layered aluminosilicates). It has been reported that montmorillonite, a variety of bentonite clays, is the most effective and promising among layered silicates. Its main characteristic is its ability to split into individual nanosized plates [22].
- (ii) Nano-oxides. Nanoparticles of titanium have been applied for this purpose [23]. They create a fire retardant barrier on wood surfaces which retard flame spread and suppress smoke generation. Additionally, during the fire, they produce water and gases which provide a cooling effect by snuffing out the oxygen. At the same time, char is created, which in turn protects the wood surface from combustion [24]. Another nano-oxide with promising potential is ZnO [25].
- (iii) Nanosilicasol and silicon compounds. Nano- SiO_2 was impregnated into the wood by the sol-gel method and demonstrated great potential [26].
- (iv) Nanostructured carbon materials. The information on carbon nanotubes and graphenes as potential materials for fire retardants is limited.

From another perspective, the wood-based composite industry is in constant demand for raw materials. Therefore, different sources of natural and synthetic materials other than wood and ligno-cellulose materials have been studied to keep pace with the ever-growing demand for raw materials. A variety of plants have been studied and tested worldwide in composites manufacturing, including vine stalks [27], topinambur stalks [28], cotton stalks [29], bamboo and coconut chips [30,31], canola straws [32], oil palms and poppy husks [33], rice and wheat straw [34], vine prunings [35], castor stalks [36], flax and banana chips [37,38], cotton stalks [39], and even seaweeds [40]. Chicken feathers were reported to be a low-cost option to be used partially, along with wood chips and fibers [21,41–43]. The physical and mechanical properties of medium-density fiberboard (MDF) and particleboard panels produced with a proportion of chicken feathers were promising. Moreover, wood-based panels with small proportions of chicken feathers would have the potential to produce lighter panels, with adequate thermal properties (acceptable thermal conductivity values, based on the value $\lambda < 1.15 \text{ W/m} \cdot \text{K}$ which is considered to be the limit for an appropriate insulation material). All these aspects are still to be carefully examined and, therefore, the present study was carried out primarily to investigate the fire properties of particleboards with 5% and 10% feather contents. With regard to the flammability of chicken feathers, separate sets of panels were produced with 10% wollastonite content to determine to what extent it could help mitigate the negative effects of the addition of flammable feathers on the fire properties.

2. Materials and Methods

2.1. Panel Production and Specimen Preparation

Wood chips were purchased from Shahid Dr. Bahonar Composite-board Company (Gorgan city, Iran) to produce particleboards. The chips consisted of a mixture of different species, namely beech (*Fagus orientalis*), alder (*Alnus glutinosa*), maple (*Acer hyrcanum*), hornbeam (*Carpinus betulus*), and poplar (mostly *Populus nigra*) species from local forests (Amol, Iran), with the addition of 5%–7% pruning branches of the fruit gardens. Boards

were produced with a target thickness of 16 mm and 0.67 g/cm^3 density; density was kept constant for all treatments. Urea-formaldehyde (UF) resin content was 10% based on the dry weight of wood chips, or the mixture of wood chips and feathers. The viscosity of the resin was 200–400 mPa s, with a 47 s gel time, and 1.277 g/cm^3 density. The producer of UF resin was Pars Chemical Industries (Tehran, Iran). The resin was sprayed on the wood chips, or the mixture of wood chips and chicken feathers, in a laboratory rotary drum. The furnish was then pressed for six minutes in a hot press, the specific platen pressure of which was 16 MPa. The dimension of the platens was $700 \text{ mm} \times 700 \text{ mm}$. The temperature of the hot press was 175°C . Spacers, made of alloy steel 16 mm in thickness, were used on the right and left sides of panels to prevent over-pressing the furnish, and to make sure the thickness of all panels was the same.

Five replicate panels were produced for each of the six treatments. The dimensions of all panels were $450 \text{ mm} \times 450 \text{ mm} \times 16 \text{ mm}$. Five centimeters around the sides of all panels were trimmed. From each panel, two specimens were cut for each physical and mechanical test. Once cut, all specimens were conditioned for eight weeks (25°C , and $40 \pm 3\%$ relative humidity) before fire tests were carried out on them. The moisture content of specimens was $7.5 \pm 0.5\%$ at the time of testing [44].

Serine ($\text{C}_3\text{H}_7\text{NO}_3$) is the main ingredient of bird feathers. The chicken feathers were procured from a commercial chicken farm. The feathers were first washed with water containing no detergent. The separation of feather fibers from quills is expensive and elevates the production costs to a degree that would not be beneficial from an industrial point of view. Therefore, only the feathers from the body of the chickens were used; the quills in body feathers are not very thick and so are flexible enough to be used without the costly process of separation.

2.2. Wollastonite Application

Wollastonite gel was purchased from Mehrabadi Technology Company (Tehran, Iran). The chemical composition of this mineral material was the same as that previously used by Taghiyari et al. [13,16]. More than 90% of the wollastonite particles ranged from 1 to $4 \mu\text{m}$ in width and thickness, and from 5 to $25 \mu\text{m}$ in length. Based on the dry weight of the UF resin used, 10% of the wollastonite (dry weight basis) was added to the resin to be mixed using a magnetic stirrer for twenty minutes. The mixture was then sprayed on wood chips or on the mixture of wood chips and feathers in a rotary drum.

2.3. Fire-Retardant Testing Device

The idea was brought up to design and build a simple, low-cost device to carry out preliminary tests, by means of piloted ignition [6,21]. A slide fire test apparatus (SFTA) is placed in a three-wall compartment so that the burning flame is not disturbed by the movement of surrounding air. Natural gas (mainly methane CH_4 , 90%–98%) is burnt through a Bunsen-type burner (with an internal diameter of 11 mm); the burner is held at 45 degrees to the specimen for 120 s (based on requirements of standard ISO 11925-3) [45]. During the test, the times at the onset of ignition and glowing at the point closest to the piloted ignition are registered. Once the specimen has been exposed to the piloted flame for the required time (in the present study, 120 s), the slide on which the Bunsen burner is mounted is pulled back. The duration of time that a visible flame can be observed on specimens is registered as the duration of burning. The length and width of the burnt area are also measured once the specimen is cooled off.

2.4. Statistical Analysis

Two-way analysis of variance (ANOVA) was carried out using the Statistical Package for Social Sciences (SPSS version 18; 2010) for each and every fire property, to ascertain significant differences between the existing groups and treatments at the 95% level of confidence. Hierarchical cluster analysis was performed by SPSS (version 18; 2010) to

categorize treatments based on the five fire properties tested in this study. Contour and surface plots were designed using Minitab statistical software (version 16.2.2; 2010).

3. Results and Discussion

Results demonstrated a statistically significant difference between the treatments (p -value of 0.000). The lowest and highest times to the onset of ignition were observed in the panels with 10% feather content (PB-CF10%, 38 s) and wollastonite and 10% feather content (PB-W-CF10%, 63.7 s), respectively (Figure 1). The addition of chicken feathers had a significant unfavorable decreasing effect on the time to the onset of ignition. This was partially attributed to the flammable nature of chicken feathers. The addition of chicken feathers was reported to have nearly the same decreasing effect on medium-density fiberboard panels [22]. Moreover, the incompatibility of chicken feathers, as a hydrophobic keratin material [41], to a woody cell wall resulted in a low integration between wood chips and feather fibers. This was also partially instrumental in the significant decrease in the time to the onset of ignition in the panels with both feather contents of 5% and 10%.

Figure 1. Time to the onset of ignition (in seconds) in six particleboard panels made from wood chips and the two chicken feather contents of 5% and 10%, containing 10% wollastonite (PB = particleboard panels; W = panels containing wollastonite; CF = chicken feather content) (letters on each column bar represent groupings based on Duncan's multiple range test, $\alpha = 0.05$).

The addition of wollastonite resulted in no significant alteration in the time to the onset of ignition in the panels with no chicken feather content. This was quite opposite to what was studied in MDF panels previously, in which a significant and favorable increase in the time to the onset of ignition was reported [46]. In order to explain this, the mechanical properties of the two kinds of composite panels (MDF and particleboard) should also be taken into consideration. A previous study on the effects of the addition of wollastonite on the physical and mechanical properties of MDF and particleboard panels reported an increasing effect in modulus of rupture (MOR) in MDF panels, and no significant effect in particleboard panels [21]. This clearly illustrated that the effects of the addition of wollastonite on MOR and the time to the onset of ignition in the two types of panels (MDF and particleboard) were quite in agreement. It was explained for MOR values that wollastonite reinforced the resin, and that fibers had more contact points in MDF panels in comparison to the wood particles in particleboards; moreover, the adsorption energy and adsorption distance of wollastonite on cell wall polymers were in favor of better integrity in the composite panels [47]. Eventually, the MOR was significantly increased in MDF panels. The reinforcement of resin by the addition of other materials at micro- and nano-scales

has also been reported [48,49]. Similarly, it can be concluded that the same reinforcing effect of wollastonite in the resin in MDF panels ultimately increased the time to the onset of ignition. However, in particleboard panels, the integrity of the wood chips was not as improved as the wood fibers in MDF panels; therefore, wollastonite could not significantly improve this fire property.

The addition of wollastonite significantly improved the time to the onset of ignition in panels containing chicken feathers (at both content levels of 5% and 10%) (Figure 1). Though the improvement was not statistically significant in comparison to the control panels (that is, the panels containing no wollastonite and no chicken feathers), the times were significantly higher in comparison to the panels with chicken feather contents of 5% and 10% and no wollastonite content. It can be concluded that wollastonite can be recommended in particleboard panels containing chicken feathers to mitigate the negative effects of the addition of feathers and to improve the time to the onset of ignition.

In terms of the time to the onset of glowing, the results demonstrated no significant difference among the six treatment panels, with a p -value of 0.992 (Figure 2). The panels produced in the present study were all single-layer panels; that is, the wood chips in the surface and core layers consisted of chips with the same size range. This in turn meant that larger-sized chips also appeared on a random basis in the surface layers. The mixture of resin and wollastonite was sprayed on the wood particles; this meant that wollastonite existed only on the surface of the wood particles. Therefore, it can be explained that once the piloted fire has gone past the surface of each particle, the untreated wood is exposed to fire. Contrary to particleboard panels, the previous study on MDF panels illustrated a significant increase in the time to the onset of glowing in wollastonite-treated panels. This was attributed to the smaller size of the wood fibers in MDF panels in comparison to the larger size of wood particles in particleboard panels. In fact, the piloted fire should have had to pass through repeated layers of wollastonite-treated surfaces; this eventually significantly increased the glowing time in wollastonite-treated MDF panels in comparison to their particleboard panel counterparts.

Figure 2. Time to the onset of glowing (in seconds) in six particleboard panels made from wood chips and the two chicken feather contents of 5% and 10%, containing 10% wollastonite (PB = particleboard panels; W = panels containing wollastonite; CF = chicken feather content) (letters on each column bar represent groupings based on Duncan's multiple range test, $\alpha = 0.05$).

The highest and lowest duration of burning occurred in the panels with the 10% chicken feather content and the control panels, respectively (Figure 3). The addition of wollastonite significantly decreased the duration of burning in the panels with no chicken

feathers. However, no significant decrease was observed in panels with feathers, though wollastonite tended to insignificantly decrease the duration of burning in the panels with the 10% chicken feather content. Wollastonite acted as an insulating layer, and it delayed the permeation of the fire to the inner layers; therefore, it could significantly decrease the duration of burning. In the panels with containing chicken feathers, a lack of integrity in the panels (as a result of the incompatibility of the chicken feathers with wood and UF resin) put the decreasing effect of wollastonite in perspective; eventually, no significant difference was observed.

Figure 3. Duration of burning (in seconds) after the removal of piloted fire, in the six particleboard panels made from wood chips and the two chicken feather contents of 5% and 10%, containing 10% wollastonite (PB = particleboard panels; W = panels containing wollastonite; CF = chicken feather content) (letters on each column bar represent groupings based on Duncan's multiple range test, $\alpha = 0.05$).

No significant difference was observed in either the length or the width of the burnt area, though slight insignificant fluctuations occurred in both properties with no particular trend (Figure 4A,B). In a previous study on the fire properties of particleboard with different wollastonite contents, a similar lack of impact of the wollastonite on the width of the burnt area was reported [50]. Moreover, there was no statistical grouping among different treatments, showing rather no particular trend. This can indicate that wollastonite cannot significantly improve these two properties in particleboard panels.

Previous studies on the relationship between fire properties reported a high and significant correlation between the different properties [9,13]. In the present study, however, the R-squared values between the fire properties were low and statistically insignificant. In this regard, though an overall relationship among the fire properties was observed, some inconsistencies in the general trend are also obvious in the contour and surface plots (Figure 5A,B). The inconsistencies in the graphs are attributed to the opposing effect, as well as the contradictory interaction, of wollastonite and chicken feathers on the fire properties. That is, wollastonite positively affected the properties, while the addition of chicken feathers resulted in the deterioration of properties. Eventually, these contradictory interactions resulted in the discrepancies in the general trend as illustrated in the contour and surface plots.

Figure 4. Length (A) and width (B) of the burnt area (mm) after 120 s exposure to piloted fire, in six particleboard panels made from wood chips and the two chicken feather contents of 5% and 10%, containing 10% wollastonite (PB = particleboard panels; W = panels containing wollastonite; CF = chicken feather content) (letters on each column bar represent groupings based on Duncan's multiple range test, $\alpha = 0.05$).

Based on the five fire properties studied here (including the times to the onset of ignition and glowing, the duration of burning, and the length and width of the burnt area), a cluster analysis was performed (Figure 6). The dendrogram illustrated the close clustering of the control panels with no wollastonite and feather contents (PB panels) to the panels containing wollastonite and 5% of feathers (PB-W-CF5%). However, the panels with 5% feathers and no wollastonite content were clustered quite remotely from the control panels (PB panels). This demonstrated the improving effect of wollastonite on the fire properties of panels that contained a low amount of feathers (i.e., 5%). This indicates that wollastonite could positively mitigate the negative effects of the addition of feathers in the panels. The panels containing 10% feathers (both with and without wollastonite) were remotely clustered from the control panels (PB panels), demonstrating that the positive effects of the addition of 10% wollastonite to the resin could not mitigate the negative

effects of the feathers on the flammability of panels. Still, the two panels with 10% feather content were distinctly clustered remotely from each other. This in turn indicates that wollastonite was effective in improving the fire properties in the panels, though the degree of effectiveness was not so high as to fully eliminate the negative effects of the 10% feather content on the flammability of panels. In a previous study on the physical and mechanical properties of MDF and particleboard panels containing 5% and 10% chicken feathers, it was reported that the 10% feather content significantly deteriorated the physical and mechanical properties to the extent that the addition of wollastonite could not mitigate the negative effects [21]. However, wollastonite was reported to successfully improve the physical and mechanical properties to acceptable levels in the panels containing 5% feathers.

Figure 5. Contour (A) and surface (B) plots between the fire properties tested in the six particleboard panels made from wood chips and chicken feathers containing 10% wollastonite.

Figure 6. Cluster analysis of the six types of particleboard panels made from wood chips and chicken feathers and containing 10% wollastonite, based on the five fire properties (PB = particleboard; W = wollastonite; CF = chicken feather content).

Based on the tests and results of the abovementioned experiment, it was concluded that a 5% content of chicken feathers can be considered an optimum level, enough to meet part of the ever-growing need for new sources of raw material in particleboard manufacturing factories, without sacrificing the important fire properties. Moreover, the addition of 10% wollastonite is recommended to significantly improve the fire properties, making the panels more secure in applications with higher risk of fire. However, a chicken feather content of 10% is not recommended, as the results of this study suggest that it leads to a significant deterioration of all properties (including physical, mechanical, and fire properties).

4. Conclusions

The present study focused on the effects of the addition of 5% and 10% chicken feathers on the fire properties of particleboard panels. Moreover, separate panels were produced with 10% wollastonite to help mitigate the probable negative effects of the addition of chicken feathers. Results demonstrated a significant deterioration of the fire properties in the panels with 10% chicken feather content. The addition of wollastonite could not help mitigate the negative effects of the incompatibility of the feathers in panels with 10% feather content. It was concluded that particleboard panels with 10% chicken feathers were not acceptable. The chicken feather content of 5% seemed to be a good option to partially satisfy the ever-growing need for natural materials, and to keep the fire properties of panels at an acceptable level as well. The opposing effects of the addition of wollastonite on one side, and chicken feathers on the other side, resulted in no significant correlation between the fire properties. Alternative resin systems such as isocyanate resins and the application of other silicate materials may be an avenue for further exploration.

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