Development of lightweight fire resistant sandwich panel

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Abstract. Fire resistant panel is one of the crucial element used to construct building components such as fire partition wall, fire door and ceiling. These fire resistant building components function as passive fire protection method to prevent the spread of smoke and fire, and to allow emergency escape of dwellers. Current challenges associated with existing fire resistant panels are heavy, labor and time inefficient. In this research fire resistant sandwich panels which are lighter in density were invented without compromising the fire resistant performance. Three fire resistant sandwich panels with various thickness were produced for two hours fire rated testing. Fire resistant sandwich panels were fabricated using respective mix proportion of vermiculite and consolidated with intumescent binder via molding techniques. Temperature profiles of fire resistant panels were recorded, plotted and analyzed. Fire resistant sandwich panel with optimum outcomes was determined by density, fire resistant performance, heat transmission rate, adhesion strength and flexural strength. Fire resistant sandwich panel Z obtained the best results in overall. Fire panel Z achieved a maximum temperature at only 83.2 °C in the Bunsen burner test, indicating a higher fire resistivity with lower heat transmission rate. Panel Z had the highest flexural strength and better fire endurance and yet with the lowest density of 578.98 kg/m³. This research revealed formulation of fire-resistant sandwich panel was the key manipulating factor to density and fire resistivity.

1. Introduction

Fire resistivity of materials is one of the key criteria in building and construction industry as fire safety measures in accordance with BS 476. This is to enforce the application of less combustible materials and to prevent the propagation of fire and surface spreading flame, while maintaining sufficient evacuation time for occupants to escape from the building during fire incident [1]. Fire resistant panel was developed and integrated onto various components of buildings like doors, walls, partitions, and ceilings to deter the growth of fire and smoke across different spaces and internal compartments within the building [2]. Fire resistant performance of panel is determined by the specific fire rating designed for it. Fire resistant panel with one hour fire rating is expected to allow minimum duration for the fire brigade to conduct emergency rescue operation for victims who trapped in building fire. Current fire resistant panels use in the market offer at least thirty minutes to one hour of critical fire rating that comply with building regulations and by-laws. Key considerations when developing and manufacturing fire resistant board are fire resistant performance and weight. Other factors for instance, acoustic, water-resistant and environmental friendliness are also taken into account. Traditional fire resistant panels used to create fire resistant building components are very weighty. Heavy panel will...
incurs difficulty in handling and installation, higher manpower and labor cost. Heavy panels will lead to expensive transportation cost due to additional fuel needed to carry these heavy materials. Extra burning of fuel moreover will increase the emission of carbon monoxide to the surrounding that will contribute to greenhouse effect, global warming which are not environmental friendly.

Calcium silicate, gypsum plaster and vermiculite are three common porous and lightweight materials used to create fire-resistant panels, due to their ability in retaining and releasing moisture to cool down surrounding temperature upon burning. These poor heat conductors can effectively reduce the heat transmission and fire spreading [2]. Vermiculite will be selected to use in this research due to its light density and higher insulating values. Medri et al. [3] stated that vermiculite is a hydrous phyllosilicate or sheet silicates mineral. When it is heated with temperature up to 600 °C - 1000 °C, it will be expanded 8 to 20 times of its original size with Accordion-like shape granules. Vermiculite is adequate to be used as lightweight aggregate in producing concrete with upgraded fire and thermal resistance for energy efficient construction due to its natural occurring properties, i.e. particles within vermiculite are expanded and are viewed as thin plates divided by air cavities. In additional, vermiculite is a chemical inertness durable and environmental friendly material which can be used to increase sound insulation, thermal insulation and most importantly is to enhance fire resistance [4].

Water based intumescent paint will be used as binder to consolidate fire boards in this research. Water-based intumescent binder is less flammable, eco-friendly and has lower volatile organic content (VOC) as compared to solvent-based binder. It is also less hazardous and less harmful to the environment, while offering good adhesion strength and high resistant to humidity [5]. However, constant and direct exposure of water-based binder to rain will affect its chemical bonding and reduce the adhesion strength [6]. Intumescent paint has been used as passive protection in building industry to protect dwellers and properties from fire [7, 8]. It consists of three main ingredients: ammonium polyphosphate (APP) an acid source, Melamine (MEL) a blowing agent and Pentaerythritol (PER) a charring agent [9]. APP will break down to phosphoric acid upon heating and trigger the PER to form thermally stable, carbonaceous char layers. APP meanwhile will release ammonia gas to expand the porous char to form a heat insulating layer to protect object underneath from fire, and reduce the tendency of structural degradation of buildings [10, 11]. Addition of synergistic agent like expandable graphite (EG) in sufficient amount in intumescent paint will yield better fire resistant performance [12-13]. EG is able to expand 100 times more than its original size in burning. Calcium carbonate (CaCO₃) functions as an extra blowing agent for charring which will lead to the improvement of char thickness, adhesion strength, and more balance temperature [14]. However, CaCO₃ will induce further chemical reaction by removing App which reduce the effectiveness of char forming mechanism, and thus poor fire resistant performance [15]. CaCO₃ might also reduce the tensile strength of paint due to its large particle size [16]. Halogen-free, inorganic fillers like aluminum hydroxide Al(OH)₃ and magnesium hydroxide Mg(OH)₂ added in appropriate quantity could improve fire and water resistant performance, thermal stability and prevent melt dripping upon burning [17-19]. However, the existence of Al(OH)₃ might decreased the adhesion strength [20]. Physical and chemical properties of all intumescent paint ingredients need to be optimized to create an effective fire protective charring layer.

Appropriate composition of APP, MEL, PER, EG, calcium carbonate and aluminum hydroxide and other ingredients will be selected to formulate water-based intumescent binder. The proportion and percentage of intumescent ingredients applied to all panels as disclosed in Table 1. This research will explore into using vermiculite core consolidated with water-based intumescent polymer binder, mortar, microfiber and plywood with the aim to develop lightweight fire resistance sandwich panels with enhanced fire resistivity. Fire resistivity of panels were examined via Bunsen burner tests. Fire resistant performance, density, adhesion strength, flexural strength and structural integrity of developed fire panels were studied.
2. Experimental works and materials

Experimental works included design and fabrication of steel mold and fire resistant sandwich panels, synthesis of water-based intumescent binder, Bunsen burner test and adhesion strength test. Three fire resistant sandwich panels were produced in this research.

2.1. Steel mold design

Steel mold was designed and digitalized using SOLIDWORKS software. Steel mold design as shown in Figure 1 was used for actual fabrication to produce fire sandwich panel X, Y and with standard dimension of 300 mm in length(L), 300 mm in width(W) and different maximum thickness (T) of not more than 55 mm.

![Figure 1. Steel mold design illustration.](image)

2.2. Water-based intumescent binder synthesis

Water-based intumescent polymer binder was formulated and used to consolidate and enhance the fire resistivity of fire panels. Water-based intumescent binder was synthesized based on intumescent ingredients such as additives and mineral fillers with different mix proportion in percentage, inclusive expandable graphite (EG). Percentage of each ingredient was calculated and converted to grams in weight, measured using mass balance before poured into the container. Mixed ingredients of intumescent binder were stirred for an hour using a high speed disperse mixer to achieve a homogeneous status. Small amount of water was added during the mixing process to reduce the viscosity. A total of 3kg water-based intumescent binder was prepared. Composition of intumescent binder as shown in Table 1.

| Ingredient                  | Mix proportion (wt. %) |
|-----------------------------|------------------------|
| **Additives**               |                        |
| APP                         | 20.0                   |
| MEL                         | 20.0                   |
| PER                         | 10.0                   |
| **Fillers**                 |                        |
| Al(OH)₃                     | 2.5                    |
| CaCO₃                       | 2.0                    |
| TiO₂                        | 2.0                    |
| Ca₂SiO₄                     | 2.5                    |
| EG                          | 1.0                    |
| **Water-based polymeric binder** |             |
| VAC                         | 40.0                   |
2.3. Design of fire resistant sandwich panels

Three fire resistant panels with dimension 300mm (L) and 300mm (W) and different thickness (T) were produced for tests. Fire resistant panel illustration as shown in Figure 2. Fire resistant panel X was designed with 23 mm thick vermiculite core consolidated with intumescent binder, sandwiched by two layers of 7 mm thick mortar and finished by two layers of 4mm thick plywood, total thickness was 45 mm. Fire resistant panel Y was designed using 36 mm vermiculite core consolidated with intumescent binder, sandwiched by two layers of 2 mm thick mortar and finished by two layers of 4mm thick plywood, total thickness was 48 mm. Fire resistant panel Z consisted of 47 mm thick vermiculite core incorporated with microfiber, consolidated with intumescent binder, and finished by two layers of 4 mm thick plywood, total thickness was 55 mm. Design measurement of panel X, Y and Z as shown in Table 2.

![Figure 2. Detail of Fire resistance sandwich panel X.](image)

2.4. Fabrication of fire resistant sandwich panels

Fire resistant sandwich panel was casted using steel mold customized at the beginning. The steel mold was split carefully using a screw and separated into several parts. Surface areas of each part were cleaned with wet cloth and left to dry in room temperature. All separated parts were then wrapped with plastic film and stucked with contact tape one by one, before they were re-installed to the original state. These processes of uninstall-wrapping-re-install of steel mold were repeated for every sample before started a new casting. The core of fire panel X was formed by mixing vermiculite and water-based intumescent binder in a container and poured into the steel mold. Mixture in the steel mold was placed on a shaking table to ensure balance and equal distribution of mixture in the mold via constant vibration. The mixture was compressed to compact using a finishing trowel and left to dry for a week. The dried solid core was de-molded, all surfaces of the steel mold were cleaned. Follow the same procedures, mortar layers were casted on both sides to sandwich the vermiculite core. Additional mortar layers were used to strengthen the vermiculite core by enhancing its structural integrity and reducing its tendency of crack and fracture. Entire fire panel X was de-molded after it was completely dried. Fire panels Y and Z were produced using exactly the same methods and procedures in fire panel X.

All fire resistant sandwich panels were further enhanced by surface finishing. This step was to ensure even outer surfaces before finished by plywood layers. Surface finishing of each sample was done by filling up those uneven holes with respective vermiculite grout. Surface finishing was applied to fire panels X, Y and Z. Six pieces of 4 mm thick plywood were cut into 300 mm (L) x 300 mm (W) in the workshop. All plywood were grinded using an electric sandpaper tool to remove sawdust to achieve smooth and fine surface. Both surfaces of each fire resistant sandwich panel were attached with 300mm x 300mm x 4mm plywood using plywood glue and further fortified with nails at four corners. Fabrication of fire panels were finalized by the completion of plywood finishes. Specifications of panels X, Y and Z as tabulated in Table 2.
2.5. Adhesion strength test
Adhesion strength of water-based intumescent binder was examined. Round steel plates were polished with sand paper to gain a smoother surface. Periphery of each steel plate was wrapped with a layer of aluminum film to give it a thickness in height. Intumescent binder was apply to a round steel plate with cross sectional area of $8.03 \times 10^{-4}$ mm$^2$. 1.0 mm thick intumescent binder was coated on the surface of a steel plate. Formation of bubbles in the coatings was avoided. The coated steel plates were left to dry for 5 to 7 days. Surface area of each coated steel plate was calculated by using the diameter value measured from micrometer. Coated steel plate was attached to bare steel plate using epoxy glue. Adhered steel plates was then slowly drawn apart from each other via tensile strength testing device Instron machine, until the coating on the steel plate was cracked and broken apart. Adhesion strength (N/mm$^2$) of intumescent binder was evaluated by divided the F values (crack charge) obtained with the surface area of steel plate (F/A).

2.6. Bunsen Burner test of lightweight fire resistant sandwich panels X, Y and Z
Two small holes were made on back surface of each sample using a hammer and nail. One hole was made at the center and another hole was made at the bottom right. Thermocouple sensors were assembled to each fire resistant sandwich panel sample by fitting its respective wires into two holes made and firmed by sticky tape. Temperature profiles of each sample were measured by connecting the thermocouple sensors to a digital thermometer. Central temperature (T1) and corner temperature (T2) were recorded every minute for 120 minutes (2 hours). Burning test of all samples were set up in an enclosed environment surrounded by for safety concern and to minimize wind factor. Each sample was stabilized and kept in a fixed position using bricks. Sample was clipped and hold tightly using G-clamp in case there was any cracking happened during the test. Temperature of Bunsen burner was measured by direct burning the steel plate connected to a thermometer. Above all steps were applied to fire panels X, Y and Z.

2.7. Three points flexural test of sandwich panels X, Y and Z
Three point flexural test was conducted on fire resistant sandwich panels X, Y and Z using Instron machine. Panel X was placed on two parallel pins at specified distance of 180 mm, a loading pin with force was applied on the middle of panel. Increasing loading force was applied to panels X until it cracked. Same procedures were used for panels Y and Z. Flexural strength of panels X, Y and Z were determined. Mechanical strength of all panels were studied.

3. Results and Discussion

3.1. Adhesion strength
Intumescent binder was prepared for the adhesion strength test. Adhesion strength of intumescent binder was examined in accordance with ASTM D-4541. Intumescent binder showed a maximum

### Table 2. Design and measurements of panels X, Y and Z.

| Sample   | Dimension, L x W x T (mm) | Weight (kg) | Density (kg/m$^3$) | Sandwich Materials                          |
|----------|---------------------------|-------------|--------------------|---------------------------------------------|
| Fire panel X | 300 x 300 x 45          | 3.356       | 828.64             | 7 mm mortar + 23 mm vermiculite + 4 mm plywood |
| Fire panel Y | 300 x 300 x 48          | 3.386       | 783.79             | 2 mm mortar + 36 mm vermiculite + 4 mm plywood |
| Fire panel Z | 300 x 300 x 55          | 2.866       | 578.98             | 55 mm vermiculite + microfibers + 4 mm plywood |
loading capacity of 2350 N and extension length of 0.79 mm at maximum tensile strength. Intumescent binder indicated an adhesion strength of 2926.53 N/mm². This revealed the intumescent binder can withstand a total weight of three adults without fracture. Intumescent binder applied to fire resistant panels in this research had achieved the desired structural bonding strength.

3.2 Bunsen burner test

3.2.1. Comparison of fire resistant sandwich panels X, Y and Z under Bunsen burner test. T1 and T2 of fire panel X were the highest at the beginning due to the changed of new Bunsen burner in the test. They started with slightly higher temperature thus ended up with slightly higher temperature. T1 and T2 of fire panel X, Y and Z were assumed to be started at room temperature of 28 ºC in this comparison analysis. Graph of temperature versus time factor of three samples as shown in Figure 3. T1 of fire panel Y was lower than fire panel Z after 30 minutes. This could be due to the additional 2 mm mortar layers coated to panel Y that are able to hinder heat transfer at initial stage. However, the increasing temperature rate of fire panel Y was the highest 0.45 ºC per minute, as compared to fire panel Z 0.35 ºC and fire panel X 0.43 ºC respectively. This could be subjected to the additional 7 mm mortar layers added to sandwich core X gave it a lower increment rate than Y. Thicker mortar layers slowed down the transferred of heat in panel X. Panel Y with 2 mm mortar layers reduced in heat resistant when further heating after 30 minutes gave it a higher temperature increment rate than X.

Temperatures of fire panels X and Y were 19.9% and 10.1% higher than fire panel Z after 120 minutes. Various temperature increment rate could be attributed to different structural layer design and thickness of fire panel X, Y and Z. Total thickness of panel X, Y and Z were 45 mm, 48 mm, and 55 mm respectively. Fire panel X had the highest end temperature at 103.1 ºC. This could be highly related to its thin thickness of vermiculite core of 23 mm as compared to Y which was 36 mm and Z which was 47 mm. Thin thickness of vermiculite core led to weak heat insulation performance of panel X. Fire panel Z had the thickest vermiculite core showed the best performance of heat insulation with end temperature at only 83.2 ºC following by panel Y 93.3 ºC. Although panel Z had the thickest vermiculite core, it was the lightest and with the best fire resistant performance. Fire panel Z was 35% and 43% lighter than fire panel Y and X. Thickness of vermiculite core played an important role in fire resistant performance in this research. Besides, microfibers added into vermiculite core of panel Z were believed to further assist in slowing down the heat transmission rate by melting and forming air bubbles in the burning process [21]. Melted microfibers contributed in enhancing mechanical strength of panel Z by bridging and binding the vermiculite particles and ameliorating any internal micro cracks that may happened in the core.

Figure 3. Temperature versus time of fire panel X, Y, Z.
Fire resistant performance of panels X, Y and Z were further enhanced with the used of intumescent binder as consolidation agent. Intumescent binder in fire panels consisted of three halogen-free additives: APP, MEL and PER. APP broke down to yield mineral acid, triggered the dehydration of PER to produce carbon char, followed by the decomposition of MER to yield gaseous component causing the char to swell forming a multi-cellular insulating layer to slow down the heat transfer. The formulation of intumescent binder was fixed in this research and same formulation of intumescent binder was applied to all panels as control parameter. Temperature increment rate of all panels as shown in Table 3.

| Sample    | Temperature Rise rating (°C) |
|-----------|-----------------------------|
|           | 30 (mins) | 60 (mins) | 90 (mins) | 120 (mins) |
| T1        | T2        | T1        | T2        | T1        | T2        | T1        | T2        |
| Fire panel X | 72.5     | 34.7     | 86.9     | 42.7     | 98.7     | 40.6     | 103.1    | 39.9    |
| Fire panel Y | 50.6     | 29.7     | 70.8     | 31.5     | 77.7     | 32.6     | 93.3     | 41.3    |
| Fire panel Z | 59.2     | 31.6     | 74.6     | 32.6     | 80.8     | 33.5     | 83.2     | 34.1    |

3.3. Fire endurance
Under fire endurance test, all fire panels were exposed to burning temperature of 1200 °C on center spot for 120 minutes. In this research, fire endurance tests were conducted concurrently with Bunsen burner test and observations were made. Small scale Bunsen burner with heating temperature of 1200 °C were used. Unnoticeable smoke with mild odor was observed during burning of fire panels X, Y and Z. No structural failure was observed for panels X, Y and Z.

3.4. Three points flexural test of panels X, Y and Z
Panel Z exhibited the highest maximum load of 103.7667 N compared to panel Y 80.9661 N and panel X 65.8119 N as shown in Table 4. Panel Z had the highest flexural stress of 1.7931 MPa and maximum extension of 6.007 mm compared to panel X 1.1372 MPa and Y 1.3991 MPa as shown in Figure 4. Panel Z displayed the highest mechanical strength and fracture toughness that it was able to withstand an increasing force up to 103.7667 N before cracked. These scenarios could be closely related to microfibers added into panel Z which gave it a higher bending strength to accommodate additional load. Studies reported incorporation of microfibers assisted in bridging materials and enhancing mechanical strength [21]. Microfibers when melted during burning will further enhance the bonding strength of particles and ameliorate micro and macro cracking to prevent fracture [21]. Thickest vermiculite core of 55 mm of panel Z gave it a higher bending extension among all [22]. Besides, intumescent binder as consolidation agent further enhanced the loading capacity and structure bonding strength of the panel. All panels fulfilled the minimum flexural stress standard of more than 1.0 MPa [23]. Results demonstrated thickness of panel, microfibers and intumescent binder play significant roles to the mechanical strength of panels.

| Sample    | Maximum Load (N) | Maximum Extension (mm) |
|-----------|------------------|------------------------|
| Fire Panel X | 65.8119    | 3.560                  |
| Fire Panel Y | 80.9661    | 4.523                  |
| Fire Panel Z | 103.7667   | 6.007                  |
4. Conclusion
Data revealed fire panel Z had achieved a better overall performance as compared to fire panel X and Y after 120 minutes of heating. Density of fire panel Z was the lightest 578.98 kg/m³, with the lowest maximum temperature reached at 83.2 °C. Loading capacity and structural strength of fire panel Z was further enhanced by intumescent binder that able to bear a maximum load of 2926 N/mm². Designed thickness, composition of vermiculite, intumescent binder, and polymer microfibers applied to fire panel Z in this research were the manipulating factors to density, fire resistant performance, adhesion strength and mechanical strength. The use of vermiculite and intumescent binder to create lighter fire resistant panel for various fire resistant building components are an innovative approach. This approach has high tendency to ensure outcome with a more promising fire resistant performance which is time-labor-transportation efficient and without compromising the environmental friendliness. This research also revealed, lightweight fire resistant sandwich panel has high flexibility to be custom-made, formulated and fabricated based on preferable performance and outcome. Lightweight fire resistant sandwich panel Z has the potential to further develop for industrial use in future.

Acknowledgement
The authors would like to thank Universiti Tunku Abdul Rahman for the financial support under the Universiti Tunku Abdul Rahman Research Fund (UTARRF) project no. IPSR/RMC/UTARRF/2017-C2/Y03) and sponsorship to the publication of this conference proceeding paper.

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Figure 4. Three points flexural test of fire sandwich panels X, Y, Z.
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