Thermally Bonded PET–Basalt Sandwich Composites for Heat Pipeline Protection: Preparation, Stab Resisting, and Thermal-Insulating Properties

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Abstract: In order to solve the cost and bulky problems of buried thermal pipeline insulating materials, this study adopts basalt fabric and low-melting PET nonwoven to construct low-cost and light-weight pipeline thermal-insulating composites after needle punching and thermal bonding processes. Research result shows that thermal-bonded temperature affected the stab resistance and burst energy more significantly. As thermal-bonded temperature increased, knife resistance and spike resistance presented the upward and then downward trends, but the burst energy gradually decreased. Yarn pull-out result shows that the enhancement of stab resistance of intra-/inter-thermal-bonded structure resulted from the increment in the coefficient of friction between yarns. When PET–basalt sandwich composites were thermal-bonded at 140 °C for 5 min, the maximum knife and spike resistance were 147.00 N (1.99 J) and 196.30 N (1.11 J), respectively, and burst energy was 4.79 J, thermal conductivity reduced to 0.0073 W/(m·K). The resultant thermally bonded sandwich composites can be used as thermal-insulating protection for buried thermal pipeline.

Keywords: thermal insulation; thermal pipeline; stab resistance; burst; thermal bonding; needle punching

1. Introduction

With the quickened progress of urbanization, the ground space becomes more and more constrained. Thermal pipelines buried to transport thermal energy are increasingly common. However, in the transportation of hot water and steam, long transmission distance results in thermal energy consumption [1]. Most available thermal pipeline insulation on the market are commonly light calcium silicate, rock wool, aluminium silicate, and polyurethane, and thermal conductivity is about 0.053, 0.052, 0.036, and 0.018–0.024 W/(m·K) [2]. However, most of these materials are rigid and hard-processable, and mineral fibers are harmful to the human body. Moreover, polyurethane foam has brittle cells, where unstable volume affects the service life and quality of thermal pipeline. Therefore, thermal pipeline insulation materials that are harmless and with high thermal insulation have been focused
on in the studies. Under this background, thermal insulating composites completely made of fibers are proposed.

As an inorganic fiber, basalt fiber has good strength, modulus, better strain to failure, high thermal insulation, good chemical resistance, are easily processed, eco-friendly, and inexpensive [3–8]. Moreover, nonwoven technology produces a fibrous porous structure that stores static air and also can form a more compact structure by carrying the surficial fibers into the interlayers. All these can be beneficial to increment in thermal insulation. As reported by researchers, fibrous thermal insulating nonwovens can be affected by fiber diameter, volume fraction, fiber conductivity, and fiber radiation [9–11]. Mohammadi et al. indicated that affecting parameters of the thermal insulation model include fabric weight, thickness, porosity, and structure, along with the applied temperature [12]. Based on these, thermal-bonded temperature and time of low-melting point affected the porosity and structure of the resultant composites. Besides this, thermal pipeline insulation materials are also subjected to sharp-objected damages when buried in the soil. Therefore, the sandwich composites structure proposed in this study has superiority in low cost, thermal insulating, and resisting against the diversified mechanical failures from knife, spike, and burst-shaped weapons. In this study, we will focus on discussing the influences of hot-baking temperature and time on quasi-static knife resistance, spike resistance, and burst strength of sandwich composites, which are made by low-melting PET nonwoven as well as basalt fabric, and reinforced by needle punching and thermal bonding. Moreover, the reason for enhancement of stab resistance is interpreted by yarn pull-out test [13–15]. Thermal insulating performance of sandwich composites is also explored.

2. Experimental Section

2.1. Materials and Methods

Low-melting point nonwoven (LPET nonwoven) purchased from Hsinjy Nonwoven Limited Liability Company, Taichung, Taiwan) has an areal density (AD) of 400 g/m², and a fiber fineness of 4 Denier (D). The maximum hot-resistance temperature and melting enthalpy of LPET nonwoven are 254.5 °C and 0.8707 mW/mg as displayed in Figure 1. Basalt plain fabric (BF fabric, Chin Carbon Fiber Technology Co., Ltd., Yixing, China) has a warp density of 50 counts/10 cm, a weft density of 49 counts/10 cm, and AD of 251 g/m².

![Figure 1. DSC curves of low-melting point nonwoven (LPET) nonwoven after heating at 10 °C/min from 30 °C to 300 °C.](image)

Two surface layers of LPET nonwoven fabrics and one interlayer of basalt plain woven fabric (BF) are laminated and needle punched using a RSZ-80 needle punching machine (Romseen Non-woven Machinery, Changshu, China). The triangular felting needle is 15 × 16 × 25 × 3 1/2 M332 G 53017
(Groz-Beckert, Baden-Wuerttemberg, Germany) with a total length of 3.5 inch as well as two of needle edges with three barbs and one of edges with two barbs in medium arrangement. Needle density is 150 needles/cm$^2$, and needle depth is 6.5 mm according to our previous research results [16]. The laminated sandwich composites are thermally treated at different temperature (100, 120, 140, 160 °C) and time (1, 5, 10, 15 min) within a self-made hot-baking mould. The structure of PET–BF sandwich composites is shown in Figure 2. The processing parameters and specifications of all samples are displayed in Table 1.

![Figure 2](image-url). Structural diagram of sandwich composites which are composed of LPET nonwovens (upper and lower layer) and basalt plain fabric (BF fabric; interface layer) after needle punching and hot backing process.

| Sample Code | Temperature (°C) | Time (min) | Thickness (mm) | AD (g/m$^2$) |
|-------------|------------------|------------|----------------|-------------|
| 1           | 100              | 5          | 3.57           | 1050        |
| 2           | 120              | 5          | 3.56           | 1050        |
| 3           | 140              | 5          | 3.55           | 1050        |
| 4           | 160              | 5          | 3.55           | 1050        |
| 5           | 120              | 1          | 3.57           | 1050        |
| 6           | 120              | 5          | 3.56           | 1050        |
| 7           | 120              | 10         | 3.55           | 1050        |
| 8           | 120              | 15         | 3.54           | 1050        |

2.2. Measurements

The quasi-static stab resistances of samples are measured at 508 mm/min using a computer servo control material testing machine (HT-2402, HungTa Intrument Co., Ltd., Taichung City, Taiwan) as specified in ASTM F1342-05 [17]. The testing heads have two types, including spike head and knife head, as shown in Figure 3a,b. The testing environmental temperature is 23 °C and the relative humidity is 53%. Samples have a size of 100 mm × 100 mm. Six samples for each specification are used for the test. The burst property of samples is tested at 100 mm/min using a computer servo control material testing machine (HT-2402, HungTa Intrument Co., Ltd., Taichung City, Taiwan) as specified in ASTM D3787 [18]. The specification of burst head is displayed in Figure 3c. The sample has a size of 150 mm × 150 mm. Five samples for each specification are used for this test. An example of installation diagram of spike head is displayed in Figure 3d, the same as that of knife head and burst head.

The yarn pull-out test of samples is tested at 100 mm/min using a computer servo control material testing machine (HT-2402, HungTa Instrument Co., Ltd., Taichung City, Taiwan). The samples have a size of 100 mm × 100 mm. The 40 mm-length free ends of yarns are reserved for the clamp between
upper fixtures. Three samples for each specification are repeatedly measured. The sample fixtures of yarn pull-out test are shown in Figure 4.

**Figure 3.** (a–c) shows the quasi-static testing head for spike stab, knife stab, and burst, and (d) shows the examples of installation drawing of spike head.

**Figure 4.** Yarn pull-out clamp of samples. (a) Model diagram of the clamp; (b,c) assembly and part pictures of practical clamp.
Thermal insulation of samples is measured by a DXR-I-SPB thermal conductivity tester (Xiangtan Huafeng Equipment Manufacture Co. Ltd., Xiangtan, China) as specified in ASTM C177 [19]. The hot plate temperature is set as 100 °C and 150 °C based on ASTM C1058. Samples have size of 200 mm × 200 mm. Three samples for each specification are tested for the mean value of thermal conductivity. The testing apparatus is displayed in Figure 5, and thermal conductivity is calculated as follows:

\[ q = m(t_2 - t_1)CL = \lambda A(T_2 - T_1) \]  
\[ \lambda = \frac{m(t_2 - t_1)CL}{A(T_2 - T_1)} \]  

where \( q \) is heat flow, \( A \) is area, \( L \) is thickness, \( T_1 \) is cold-plate temperature, \( T_2 \) is hot-plate temperature, \( m \) is average flow of cold water in center calorimeter, \( C \) is water specific heat capacity (4.2 × 10^3 J/kg), and \( t_1 \) and \( t_2 \) are respectively inlet temperature and outlet temperature of cold water.

Figure 5. The testing apparatus for thermal insulation.

3. Results and Discussion

3.1. Effects of Thermal-Bonded Time and Temperature on Knife Stab Resistance

Figure 6a,b shows the knife stab resistances with different thermal-bonded time and temperature. The hot-baking time is changed as 1, 5, 10, and 15 min when the sandwich composites are thermally treated at 120 °C. The hot-baking temperature is varied as 100, 120, 140, and 160 °C when the composites are thermally treated for 5 min. Comparatively, knife-resistance force and energy of thermal treatment for 5 min are larger than other thermal durations, which represents the best knife-resistance performance. Under the action of knife, surficial nonwoven and interlayer BF are both damaged, and the failure surface presents a thin and long cut, which results from the cutting, friction between yarns, and friction between knife and yarns, as well as tensile plastic deformation [20]. The higher friction coefficient between yarns can generate a larger knife-resistance load and energy [21]. With shorter hot-baking time, the effect of plastic deformation to knife resistance is bigger than the yarn slippage and friction between knife and surface of composites. After longer hot-baking time, LPET fibers are thermally bonded with each other. The plastic deformation becomes smaller, and the friction between knife and composites exhibits to be greater. However, the contributions of plastic deformation and friction to the sandwich composites were distinct at different thermally bonded time; therefore, 5 min showed the maximum knife energy as presented in Figure 6a. With higher temperature, the knife force and energy both firstly increase and then decrease as seen in Figure 6b. This is because heat transmission needs a certain duration; at lower temperature the interlayer LPET fibers cannot melt completely, but at much higher temperature, all LPET fibers in the composite reached melting points,
and fiber structure was completely damaged, which produced the smallest plastic deformation and lower knife energy. Comprehensively speaking, thermal bonding at 140 °C possesses the biggest knife-resistance force and energy.

![Figure 6](image6.png)

**Figure 6.** Knife-resistance force and energy of sandwich composites with different (a) hot-baking time and (b) hot-baking temperature.

Typical knife displacement–load curves with different thermal-bonded time and temperature are reported in Figure 7. Two sets of data with different time and temperature are similar. They are both divided into two steps. The first stage is due to the fibers cutting and friction force between knife head and composites. In this stage, the knife firstly slides apart the fibers and then cuts the original contacting regions of fibers. It can be seen from Figure 6a,b that the fibers separation becomes more difficult at higher temperature and longer time, which results in an obvious first peak in the first stage. The maximum peak occurs when the original contacting fibers are cut. As the knife penetrated deeply, the cutting fibers and friction between cutting fibers continuously increased, which in turn increased the knife-resistance force.

![Figure 7](image7.png)

**Figure 7.** Typical knife-resistance curves of composites thermal-bonded at (a) different time and (b) different temperature.

### 3.2. Effects of Thermal-Bonded Time and Temperature on Spike Stab Resistance

Figure 8 shows the spike-resistance results of sandwich composites. Figure 8a displays the spike-resistance force and energy at 120 °C for different thermal-bonded time, and Figure 8b reveals those at different temperature for 5 min. Both of them exhibit the climbing up and then down trends with increase in thermal-bonded temperature and time. This demonstrated the double-sided effects of thermal bonding. At higher temperature or longer time, the thermal-bonded area became
bigger, leading to more compact structure in composites. However, when surpassing a certain value, completely melting LPET fibers make the composite brittle and breaking elongation small. These changes reduced the friction and deformation between spike head and composites and then conversely decreased the spike resistance [22]. The maximum spike-resistance force and energy is 196.3 N and 1.11 J when PET–BF composites were thermally bonded at 140 °C for 5 min.

Figure 8. Spike-resistance force and energy of PET–BF sandwich composites after thermal-bonding at different time (a) and temperature (b).

Figure 9 displays the typical spike-resistance curves of PET–BF sandwich composites. The spike depressed the surface of whole composites as displacement increases. At the moment that compression deformation energy reaches the maximum and the friction changes from static friction to dynamic friction, the spike resistance achieves the maximum value [23]. This accords with our previous study, which indicated that the friction was the main mechanism for spike resistance [24]. Therefore, even with varying temperature and time, the spike resistance responds in similar behaviors.

Figure 9. Typical spike-resistance curves of composites thermal-bonded at different time (a) and different temperature (b).

3.3. Effects of Thermal-Bonded Time and Temperature on Burst Property

Figure 10 shows bursting strength and energy of PET–BF sandwich composites. Different from knife and spike experimental results, bursting strength and energy both decrease with thermal-bonded temperature (see Figure 10b). This is because the burst failure mode was yarn pull-out, fracture, and nonwoven deformation, not the same as stab resistance, as indicated by Yan et al. [25]. However, being thermal-bonded at 120 °C, 10 min duration reveals the minimum burst energy. This decrease
of burst energy has no significance in the influence of temperature to burst energy. It reflects that thermal-bonded temperature affected burst energy more significantly than time. The maximum burst strength and energy happen at 100 °C for 5 min, reaching 1511.25 N and 8.82 J, respectively, when sandwich composites generate the maximum deformation.

Figure 10. (a) Burst force and (b) energy of PET–BF sandwich composites after thermal-bonding at different time and temperature.

3.4. Effect of Thermal-Bonded Temperature on Yarn-Out Force

In order to deeply study on effect of thermal-bonded temperature on the stab resistance and burst property, the fracture planes of sandwich composites after knife damage are observed in Figure 11 using Tabletop Microscope 1000 (Hitachi, Japan). It can be seen from Figure 11a that when composites were thermally bonded at 100 °C, most of the fiber ends generated cut deformation and remained in the fiber state. As thermal-bonding temperature increased from 120 °C to 140 °C, thermal-bonding area became bigger and thermal-bonding points distributed uniformly, as seen in the red circles in Figure 11b,c. When composites were thermal-bonded at 160 °C, LPET lost their fiber shape, and conversely, a relatively bigger void was found, which can explain the decreased tendency of knife resistance and spike resistance as function of thermal-bonded temperature in Figures 6b and 8b. Thermal-bonding points can increase the fibers cohesion and decrease the inter-fiber slippage, which is beneficial to improve the stab resistances and their stability [26]. However, when surpassing the melting point, the composites’ excessive shrinkage conversely produced a large number of voids after hot-baking, which in turn decreases the stab resistance.

The tendency of yarn pull-out force also follows the same with varying temperatures as shown in Figure 12. Compared to pure basalt fabric, the yarn pull-out force at 140 °C is increased by one time. Using an approach similar to Coulomb friction, \( f = \mu F \), the pull-out force \( f \) is proportional to coefficient of friction \( \mu \) at the same applied pre-load perpendicular to the pull-out force \( F \). Therefore, higher pull-out force corresponded to the bigger coefficient of friction. Figure 12 shows the static and dynamic forces of friction as related to displacement. Figure 12a displays significant static and kinetic friction forces, but Figure 12a reveals that the kinetic friction force becomes insignificant because vertical needle-bonded points and thermal-bonded points limited the pull-out displacement of basalt yarns. The slopes of pull-out force after thermal-bonding at 100 °C, 120 °C, 140 °C, and 160 °C are 5.63, 4.36, 9.19, and 4.25, respectively, which shows the bonding effects from vertical tufts and thermal-bonding points and thus explains the tendency of spike and knife resistance in relation to thermal-bonded temperature.
3.5. Effect of Thermal-Bonding Temperature on Thermal Conductivity

Figure 13 shows thermal conductivity results at 100 °C and 150 °C after composites were thermally bonded at different temperatures. As thermal-bonded temperature increases, thermal conductivity at 100 °C and at 150 °C firstly decreases and then increases. This is due to the number and size of air voids reduced air convection in composites. After thermal shrinkage and bonding, melting LPET fibers can lock some static air in the LPET nonwoven and interspace between basalt fabrics.
which decreased the thermal convection. Meanwhile, static air had the lowest thermal conductivity $K_a$, 0.0243 W/(m·K), and the larger air volume fraction $V_a$ results in lower thermal conductivity $K_m$ in accordance with simple mix principle as $K_m = V_f K_f + V_a K_a$ (where $V_f$ is fiber volume fraction, $K_f$ is fiber thermal conductivity). This finding corresponds to the results indicated by Lin et al. that air convection decreased with void size in the structure. Thermal conductivities of resultant composites were all below 0.0250 W/(m·K) at testing temperature of 100 °C, much smaller than that of PET–LPET nonwoven indicated in the above-mentioned study [27]. Comparatively, increasing testing temperature to 150 °C, thermal conductivity increased to 0.0197 W/(m·K) when composites were thermally bonded at 140 °C which due to higher thermal conductivity of fibers [28].

![Figure 13. Thermal conductivity results at 100 °C and 150 °C of sandwich composites being thermal-bonded at different temperature.](image)

4. Conclusions

This study designed an intra-/inter- reinforced PET–Basalt sandwich composite structure based on the thermal bonding and needle punching process, which is used for thermal pipeline protection. Effects of thermal-bonding parameters including temperature and time on knife resistance, spike resistance, and burst property were investigated, and effect of thermal-bonded temperature on yarn pull-out forces was explored to explain the influencing mechanism. Thermal conductivity of all samples was also discussed.

Stab resistance results showed that thermal-bonded temperature had more significant effect on both of knife-resistance and spike-resistance energy than thermal-bonded time. Moreover, the knife- and spike-resistance energy showed an increase and then decrease with increasing thermal-bonded time, but the burst energy steadily decreased. This difference is due to the different failure damage mechanisms. Yarn pull-out force results displayed that the tends of thermal-bonded temperature on pull-out force corresponded to those on knife and spike resistances. Moreover, the reason for increase of stab resistance from thermal-bonded temperature was due to higher coefficient of friction between yarns. Thermal conductivity showed that the lowest thermal conductivity was 0.0073 W/(m·K) at setting temperature of 100 °C. According to the stab resistance, burst property, and thermal insulation, the resultant sandwich composites can be used for thermal insulation of pipeline in the future.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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