Isı Bilimi ve Tekniği Dergisi, 42, 2, 245-256, 2022
J. of Thermal Science and Technology

ISSN 1300-3615
https://doi.org/10.47480/isibted.1195019

FINDING CONDITIONS IN REPROCESSING OF GLASS WOOL WASTE AS A HEAT INSULATOR

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(Geliş Tarihi: 29.03.2022, Kabul Tarihi: 03.10.2022)

Abstract: This research aimed to find the process of value adding for glass wool waste from the glass wool composite board used in the vehicle industry. The waste was reprocessed to be an insulator and to determine the suitable conditions for hot-press forming to create new materials having high thermal resistant properties. Firstly, the properties of the original board; the thermal resistances (R) and the noise absorption coefficients (NRC), were measured and were found averages of 0.9055 m^2K/W and 0.3955, respectively. The reprocessing conditions were varied by 2 levels; high and low, of 5 control factors; density, thickness, pressure, temperature, and surface roughness. Three repeating processes for each condition were performed. The Design of Experiment (DoE) was the full factorials; 2^5 experiments, by using the Analysis of Variance (ANOVA) to find main and interaction factors relating to the properties. From the ANOVA results with the α level of significance at 0.05, it was found that the main factors responding to the high values of the thermal resistance were the thickness and density. This resulted in the suitable conditions for the hot-press process of both the new smooth and rough pads with a density of 96 kg/m^3 and a thickness of 25 mm. The R values of the new insulators were in between 0.88 – 0.98 m^2K/W and, additionally, the high NRC values were also provided in between 0.46 – 0.49. These findings could be applied for wall designing, wall decorations and heat shields for indoor rooms and different types of buildings.
Keywords: Glass wool waste, Insulator, Reprocessing, Heat transfer, Thermal resistance

CAM YÜNÜ ATIĞININ ISIL YALITKAN OLARAK YENİDEN PROSES EDİLMESİNİN KOŞULLARININ BULUNMASI

Özet: Bu çalışma otomotiv endüstrisinde kullanılan cam yünü kompozit levhadan elde edilen cam yünü atığının değer katma sürecini bulmayı hedeflemektedir. Atık, bir yalıtkan olması ve yüksek ısıl direnç özelliklerine sahip yeni malzemeler oluşturmak için kullanılan sıcak pres şekillendirme için uygun koşulların belirlenmesi amacıyla tekrar işlenmiştir. İlk olarak orijinal tahtanın özellikleri; ısıl direnç (R) ve gürültü emilim katsayıları (NRC) ölçülmüş ve sırasıyla ortalama 0,9055 m^2K/W ve 0,3955 olarak bulunmuştur. Tekrar işleme koşulları, yoğunluk, kalınlık, basınç, sıcaklık ve yüzey pürüzlülüğü olmak üzere 5 adet kontrol faktörüne ve yüksek ve alçak olmak üzere 2 adet seviyeye göre değişmektedir. Her koşul için üç tekrarlama işlemi gerçekleştirilmiştir. Tasarım analizi, 2^5 deneyden oluşarak, tam faktöriyeldir ve özelliklere ilişkin ana ve etkileşim faktörlerini bulmak için Varyans Analizi (ANOVA) kullanılmıştır. α anlamlılık düzeyi 0,05 olan sonuçlardan, ısıl direncin yüksek değerlerine sebebiyet veren ana faktörlerin kalınlık ve yoğunluk olduğu bulunmuştur. Bunun sonucunda hem yeni pürüzlü hem de pürüzsüz pedler için sıcak pres işlemi uygun koşullarının 25 mm kalınlık ve 96 kg/m^3 yoğunluk olduğu açığa çıkmıştır. Yeni yalıtkanların R değerleri 0,88 – 0,98 m^2K/W arasında olmaktadır ve ayrıca yüksek NRC değerleri de 0,46 – 0,49 arasında olacak şekilde verilmiştir. Bu bulgular, iç mekanlarda ve farklı bina tiplerinde duvar tasarımı, duvar dekorasyonları ve ısı kalkanları için kullanılabilir.
Anahtar Kelimeler: Cam yünü atığı, Yalıtkan, Tekrar işleme, Isı transferi, Isıl direnç

NOMENCLATURE

Symbols

R	thermal resistance (m^2 W/m)
k	thermal conductivity [W/m·K]
NRC	Noise Reduction Coefficient
SAC	Sound Absorption Coefficient
S	Standard deviation
R-sq	Explained variation / total variation

Greek Symbols

μ	overall mean
τ	The effect of factor A (surface)
β	The effect of factor B (density)
γ	The effect of factor C (temperature)
σ	The effect of factor D (thickness)
α	The effect of factor E (pressure)
ε	Random error of the experimental
ρ	density [kg/m^3]

INTRODUCTION

Climate changes have affected all countries in the world. Thailand climates fluctuate as risen atmospheric temperatures continuously. The growing amounts of energy consumption and carbon dioxide emission are main keys causing greenhouse effect and heat waves. There are many campaigns promoting energy conservation in every section such as industrial and residential sections. Green and recycle materials are recommended and investigated to be manufactured in the industrial level. These materials are considered as safe products from environmental-friendly processes which use low energy consumption in their production lines and reduce operating cost of the manufacturers. Glass wool is one of many insulators used in construction and vehicles because of its low thermal conductivity; 0.032 W/m K. Glass wool is used to pad on vehicle bodies to reduce conductive heat transfer rates from ambient into vehicle compartments helping refrigerating systems to maintain the compartment conditions. Moreover, glass wool can absorb sound and reduce noise from outside into the compartments. The International Agency for Research on Cancer, World Health Organization (WHO) certified that glass wool does not harm human health. If a glass wool fraction goes into the human respiratory system, the person will sneeze and get rid of the fraction due to its cylindrical structure is big and its diameter is approximately 7 microns. Since glass wool is commonly used in construction and vehicle industries, a great amount of glass wool waste is disposed by burning and burying in landfills each year. The Department of Industrial Works, Ministry of Industry, Thailand, encourage manufacturers to recycle and reuse waste in many forms and purposes as 3Rs (Reduce Reuse Recycle). This campaign has reduced glass wool waste but this waste; more than one million tons, has potentials to be reprocessed and utilized. The glass wool waste weights more than 20 tons. Every month, the manufacturers spent certain amount of budget to get rid of it properly. Glass wool can be formed in blanket and board both bare and covered surfaces with layers such as aluminum foil. The glass wool made according to ASTM standard and Thai Industrial standard codes can be used as insulators and acoustic in offices, dwellings, and buildings. The glass wool qualifications are 1) thermal insulation with a low thermal conductivity of 0.032 W/m K, a good thermal resistance, 2) acoustic insulation, 3) non-flammable, 4) easy installation, 5) compressive strength, 6) condensation control, 7) long life performance, and safe to use approved by WHO.

Yodkaew et al. (2007) developed acoustic ceiling by using rice shell. The developed ceilings were examined to find their Noise Reduction Coefficients (NRCs) and their NRCs were compared with those of gypsum, acoustic, and glass wool boards. Their results showed that the developed ceiling from the rice shell-to-glue ratio at 5:1 had better NRC than those of the gypsum and acoustic boards. Choowonglert and Thakkhanont (2015) developed acoustic boards from paper waste from offices. The waste was shredded by paper shredders before it was reprocessed by a hot pressing process. The reprocessed boards had thicknesses of 10, 15 and 25 mm. Noise absorption properties showed the board potentials to be developed into the commercial acoustic material which was made from the office-paper waste, environment-friendly, and nicely adding values to the waste.

Pakhunworakit et al. (2006) investigated thermal conductivity values of insulators made from agricultural waste; corn cob and cassava tree, having different density values. The best insulator was the cassava-tree insulator having the density of 200 kg/m^3, the thickness of 10 mm, the lowest thermal conductivity was found at 0.059 W/m K. Homaswin et al. (2007) developed building acoustic insulators made from coconut-shell fiber with the size of 0.5 m in height and width. The fiber insulator covered with the 2-inch latex layer provided the NRC close to that of the glass wool board and this NRC was better than those of the gypsum and acoustic boards. Narakaew and Narakaew (2015) developed activated carbon made from corn cob and boards made from hay, and the corn-cob activated carbon. The smell and noise absorptive performances were experimentally investigated by using the developed boards as walls of a one cubic meter room. The noise absorptive performance was higher than those of the walls made from acoustic foam and glass wool.

Zhao et al. (2018) presented lifecycle assessment of typical glass wool production in China, this work was aimed to reduce unnecessary energy in the glass wool production. The commercial software named eBalance which was developed by Integrated Knowledge for our Environment (IKE) was used to investigate Primary Energy Demand (PED), Global Warming Potential

(GWP), Acidification Potential (AP), Photochemical Oxide Formation Potential (POFP) and Refractive Index (RI). The lifecycle assessment analysis found that the glass wool waste mostly affected environment on energy in manufacturing processes. The GWP was 49% while the AP, POFP and RI were 50%, 25% and 39%, respectively. This research claimed that the energy conservation measures played an important role on reducing environmental impacts caused by the glass wool waste.

Jeon et al. (2017) experimentally studied effects of humidity on glass wool by measuring thermal conductivity of the glass wool specimens after they exposed to humidity. Results indicated that the non-coating glass wool or the glass wool without anti-moisture agent could absorb water about 4% - 8% of its weight and the thermal conductivity was increased 4 times higher. The coated glass wool or the glass wool covered with anti-moisture agent by Fluoroalkylsiloxane (SH-AF) technique provided the thermal conductivity at 0.0329 W/m K. Therefore, the anti-moisture agent reduced the thermal conductivity of the coated glass wool, approximately at 0.0344 W/m K.

Wajima and Matsuka (2019) presented a decomposing process for glass wool waste by using the sodium hydroxide pyrolysis. This research was aimed to reduce the waste having glass wool fibers and resin as the main components. This method was introduced as a new recycle process to reduce the waste by changing chemical components of the waste in 400 - 500 Celsius anaerobic conditions and using sodium hydroxide as a chemical catalyst. From the results, the most decomposition of the resin-glass wool waste could be found when 3 grams of the sodium hydroxide was used, the decomposition was 20% of the original weight.

Since the world focuses on the sustainable development goals, this research aimed to promote inclusive sustainable industrialization and fostering innovation and to take action to combat climate change by recycling and reprocessing the glass wool waste, as well as to ensure sustainable consumption and production patterns by producing the new insulator for building in cities and human settlements inclusive, safe, resilient and sustainable. This work paid particular attention to find reprocessing conditions to recycle the glass wool waste from the vehicle industries, to investigate properties of the reprocessed insulators and to compare the properties with the original properties of the glass wool board and the commercial one. The recreating conditions; thermal resistances (Rs) and Noise Reduction Coefficients (NRCs) were investigated and reported in this paper. The results of this research could provide necessary information for insulator manufacturers to reprocess the glass wool waste and to produce the new insulator from the waste. The recreated insulator as a composite board could be used in the construction, furniture or design industries as user demands.

METHODOLOGY

The glass wool waste was collected from a vehicle assembly factory, it was reprocessed under 5 control parameters; density, thickness, pressure, temperature, and surface roughness. Three repeating processes for each condition were performed. All reprocessed specimens were tested to find thermal conduction (k) and thermal resistance (R) followed the procedure of ASTM C518 by using sample sizes of 17.5 cm width, 17.5 cm length, and 5 cm height. Then, Sound Absorption Coefficient (SAC) and Noise Reduction Coefficient (NRC) were evaluated followed the procedure of ISO 10534-2 by using 10 cm and 3 cm diameter specimens for low and high frequency tests, respectively. In this work, the factorial design of 5 control parameters at high (+1) and low (-1) levels as shown on Table 1 was applied by using Analysis of Variance or ANOVA to reduce possible errors.

Table 1. Research factors

Control factors	Factors	Factor levels	
		Low (-)	High (+)
Surface	A	Smooth	Rough
Density (kg/m^3)	B	64	96
Temperature (°C)	C	160	190
Thickness (mm)	D	15	25
Pressure (bar)	E	10	15

The Factorial Experimental Design of the Two Power Five (2^5) was used to collect experimental data and analyze statistical results. The ANOVA significance level of the experiments was specified as $\alpha = 0.05$ from 32 conditions and 3 repeating experiments to find responses of thermal conductivity and Noise Reduction Coefficient. The total of 96 experimental units were gathered as shown on Table 2. Steps of experimental analysis consisted of two main steps.

Firstly, the linear statistical model of the two power five full factorial was defined as following (Ayuttaya, 2007);

$$\begin{aligned} y_{ijklmn} = {} & \mu + \tau_i + \beta_j + \gamma_k + \delta_l + \alpha_m \\ & + (\tau\beta)_{ij} + (\tau\gamma)_{ik} + (\tau\delta)_{il} + (\tau\alpha)_{im} \\ & + (\beta\gamma)_{jk} + (\beta\delta)_{jl} + (\beta\alpha)_{jm} \\ & + (\gamma\delta)_{kl} + (\gamma\alpha)_{km} + (\delta\alpha)_{lm} \\ & + (\tau\beta\gamma)_{ijk} + (\tau\beta\delta)_{ijl} + (\tau\beta\alpha)_{ijm} \\ & + (\tau\gamma\delta)_{ikl} + (\tau\gamma\alpha)_{ikm} + (\tau\delta\alpha)_{ilm} \\ & + (\beta\gamma\delta)_{jkl} + (\beta\gamma\alpha)_{jkm} + (\beta\delta\alpha)_{jlm} \\ & + (\gamma\delta\alpha)_{klm} + (\tau\beta\gamma\delta)_{ijkl} + (\tau\beta\gamma\alpha)_{ijkm} \\ & + (\tau\beta\gamma\delta\alpha)_{ijklm} + \varepsilon_{ijklmn} \end{aligned} \tag{1}$$

where subscripts; i, j, k, l, and m, are the effects of the low and high factors (Table 1) which can be 1 and 2, respectively. Secondly, Analysis of Variance was performed by using a commercial computer software, the trademark name was MINITAB.

EXPERIMENTAL PROCEDURES

Glass wool waste from the car-roof-insulation process in the vehicle factory was taken in a form of a composite board The insulator reprocessing steps started with taking polyester cloth covering the waste out. Polyester must be separated because it can affect environment. The waste was, then, put into a plastic granulator to make glass wool scraps. The scraps were weighted to meet the investigating density values and arranged on the designed molds; two surface types and thicknesses. Two steel plates were sandwiched on the mold surfaces before the molds were put in the hot-press machine to form the reprocessed insulators such that heat from the machine did not come into direct contact with the scraps. The machine operating conditions; temperature and compression values, were set according to the experimental designs, all experimental design factors are shown on Table 1. Since the sample roughness is one of the interesting parameters, the definition of the the sample roughness should be given. The reprocessed samples with two surface types; smooth and rough, are shown on Figure 1. The rough surface mold was prepared separately from the smooth surface mold.

Table 2. Experimental conditions

Conditions	A	B	C	D	E
1	Smooth	64	160	15	10
2	Smooth	64	160	15	15
3	Smooth	64	160	25	10
4	Smooth	64	160	25	15
5	Smooth	96	160	15	10
6	Smooth	96	160	15	15
7	Smooth	96	160	25	10
8	Smooth	96	160	25	15
9	Smooth	64	190	15	10
10	Smooth	64	190	15	15
11	Smooth	64	190	25	10
12	Smooth	64	190	25	15
13	Smooth	96	190	15	10
14	Smooth	96	190	15	15
15	Smooth	96	190	25	10
16	Smooth	96	190	25	15
17	Rough	64	160	15	10
18	Rough	64	160	15	15
19	Rough	64	160	25	10
20	Rough	64	160	25	15
21	Rough	96	160	15	10
22	Rough	96	160	15	15
23	Rough	96	160	25	10
24	Rough	96	160	25	15
25	Rough	64	190	15	10
26	Rough	64	190	15	15
27	Rough	64	190	25	10
28	Rough	64	190	25	15
29	Rough	96	190	15	10
30	Rough	96	190	15	15
31	Rough	96	190	25	10
32	Rough	96	190	25	15

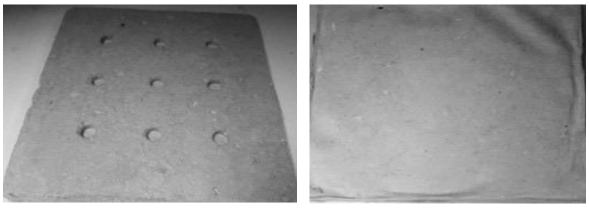


Figure 1. Reprocessed boards with two surface roughness; a rough surface (left) and a smooth surface (right)

RESULTS AND DISCUSSIONS

The insulator used in door assembly processes of vehicle industries combined of glass wool and non-woven polyester. The glass wool properties are shown in Table 3. From the information, the non-woven polyester must be separated because it can affect environment. The non-woven polyester was separated from the rest of the insulator waste. Three waste samples were investigated to find their properties at 20 and 50 Celsius as shown on Table 4, the average thermal conductivity (k) and thermal resistance (R) were 0.0166 W/mK and 0.9055 m^2K/W, respectively. The samples were also tested to find Sound Absorption Coefficient (SAC) in 4 frequency levels; 250, 500, 1000, and 2000 Hz. Noise Reduction Coefficient (NRC); the average value of 4 SACs at 23 Celsius and 50%RH, was calculated. All SACs are presented on Table 5 and the NRC was 0.3955 or approximately 0.4. The sound absorption materials or acoustic materials commonly have NRCs at 0.4 or higher. These properties can be referred as the raw material properties of the reprocessed insulator. Before the waste was reprocessed, the waste flammability test was performed by using UL95 technique (Underwriters Laboratories 95 of USA) with 5 random samples at 24 Celsius and 53 %RH. The flammability test results are shown on Table 6, no sample was burned up to the holding clamp and no cotton indicator ignited was found.

Table 3. Properties of the glass wool insulator

Information	Details
Component	Glass wool 85 – 95% Cured binder 5 – 15%
Appearance	The material is yellow that can be flexible
Smell	None
Soluable	Insoluable
Be stable and fast reaction	Stable
Information about the danger	Direct skin contact may cause irritation.

Table 4. Thermal conductivity (k) and thermal resistance (R) results of the samples

Sample Types	Thick-ness (m)	Test Temp (°C)	Test Temp (°C)	k-values (W/m K)	R-values (m^2 K/m)
Composited board (0.321±0.005 kg)	0.0156± 0.0050	20	50	0.0166 ± 0.005	0.9384
Composited board (0.321±0.005 kg)	0.0138± 0.0005	20	50	0.0141 ± 0.005	0.9769
Composited board (0.321±0.005 kg)	0.0138± 0.0005	20	50	0.0190 ± 0.005	0.8012

Table 5. Sound Absorption Coefficient (SAC) and Noise Reduction Coefficient (NRC) results of the samples

Type	Sound Absorption Coefficient (%) and NRC					
	250 Hz	500 Hz	1000 Hz	2000 Hz	Ave.	NRC
Com-posited board	7.02 %	29.3%	58.9 %	62.8 %	39.5 %	0.3955

Analysis of Variance for Thermal Conductivity (k) and Thermal Resistance (R)

All thermal conductivity (k) and thermal resistance (R) results of 96 reprocessed samples were analyzed statistically by using the data analysis, statistical and process improvement tools; Minitab as the trademark, Analysis of Variance or ANOVA was performed by considering only two-way interaction. ANOVA for the thermal resistance was performed. Firstly, the hypothesis test started with a test of main factors; H 0 and H 1 represented the main factors having no effect and having effects on the thermal resistances, respectively. Then, a test of interaction factors was carried on; H 0 and H 1 represented the interaction factors having no effect and having effects on the thermal resistances, respectively. All ANOVA results for the thermal resistance are exhibited on Table 7. Statistical testers; F–Value or F0 > F0.05, (1,64) was higher than 4.08 or P–Value was less than the significance level (α) of 0.05. The H 0 was rejected and the H 1 was accepted, the main and interaction factors had effects on the thermal conductivity of the reprocessed samples at the significance level (α) of 0.05 as following;

1) The interaction factors; B*D or density (kg/m^3) and thickness (mm), and
2) The main factor; E or compression pressure (bar).

Table 6. The results of the horizontal flame spread test of the samples

No.	Thick-ness (mm)	T_1 (s)	T_2 (s)	T_3 (s)	Sample Burn Up to Holding Clamp	Cotton indicator ignited
1	12.61	0	0	0	No	No
2	11.02	0	0	1	No	No
3	9.75	0	0	1	No	No
4	9.76	0	0	0	No	No
5	11.50	0	0	0	No	No

* T_1 T_2 and T_3 are the flame spread seconds of the three samples, respectively.

Table 7. Analysis of Variance (ANOVA) results in the thermal resistance investigation

Source	df	SS	MS	F-valve (F0)	p-value	Noted
A	1	0.00428	0.00428	0.86	0.357	
B	1	0.00767	0.00767	1.54	0.219	
C	1	0.01018	0.01018	2.04	0.158	
D	1	1.38055	1.38055	276.96	0.000	Sig.
E	1	0.02217	0.02217	4.45	0.039	Sig.
A*B	1	0.00119	0.00119	0.24	0.626	
A*C	1	0.00529	0.00529	1.06	0.306	
A*D	1	0.00304	0.00304	0.61	0.437	
A*E	1	0.00098	0.00098	0.20	0.658	
B*C	1	0.00056	0.00056	0.11	0.737	
B*D	1	0.02622	0.02622	5.26	0.025	Sig.
B*E	1	0.00067	0.000677	0.14	0.714	
C*D	1	0.00192	0.001921	0.39	0.537	
C*E	1	0.00000	0.000002	0.00	0.986	
D*E	1	0.00546	0.005469	1.10	0.299	
Error	64	0.31901	0.319018			
Total	95	1.90151				

S = 0.0706021 R-Sq = 83.22% R-Sq(adj) = 75.10%
Sig. = Significant

Secondly, Model Adequacy Checking was rendered to investigate suitability and accuracy of the information; error patterns followed the fundamental of $\varepsilon ij \sim N(0,\sigma 2)$ by using residual values. This analysis confirmed the accuracy and dependability of the information as shown on Figure 2. From the normal probability plot on Figure 2, the residual distribution was linear. The fitted value of each factor level distributed randomly and ordinarily around the center line, the residual distribution was not a megaphone pattern, this distribution implied that the data had the stability of their deviation and the data was

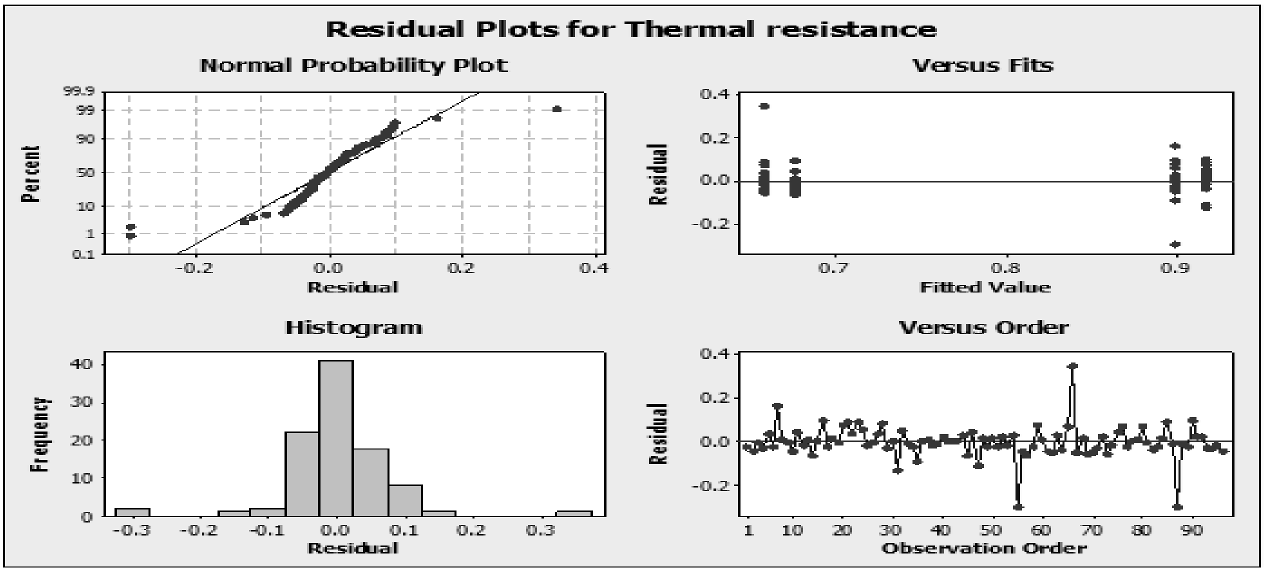


Figure 2. Residual plots in the thermal resistance investigation

independent. The residual distribution was not in any trends and patterns, the data were independent and not related to their collecting sequence**.**

Thirdly, the analysis of the interaction and main factors was performed to find the suitable factor level. From Table 7, the interaction factors; B*D, and the main factor; E, had effects on the thermal resistances. The effect of the interaction factors; B*D, on the thermal resistance (R) was considered primarily as displayed on Figure 3. The high thermal resistance was encountered when the interaction factors; B*D or density was at 96 kg/m^3 and thickness was at 25 mm. The high thermal resistance was met when the main factor; E or compression pressure was at 15 bar as shown on Figure 4. Therefore, the suitable factors responding to the thermal resistance and the hot pressed process were as following; the high level (+) of the factor; B or the density at 96 kg/m^3, the high level (+) of the factor; D or the thickness at 25 mm, and the high level (+) of the factor; E or the compression pressure at 15 bar. as shown on Figure 4. Therefore, the suitable factors responding to the thermal resistance and the hot pressed process were as following; the high level (+) of the factor; B or the density at 96 kg/m3, the high level (+) of the factor; D or the thickness at 25 mm, and the high level (+) of the factor; E or the compression pressure at 15 bar. These factors could be used as the conditions of the reprocessing process and the highest average thermal resistance was obtained from the 16th condition on Table 8 as 0.98028 K/W.

Table 8. Conditions providing the high thermal resistances of the reprocessed insulators

Conditions	**Thermal Resistances**			**Average**
	Numbers of Replicate			
	1	**2**	**3**	
8	0.89854	0.94529	0.98804	0.94396
16	1.0172	0.93574	0.9879	0.98028
24	1.0028	0.92499	0.94249	0.95676
32	0.96683	0.88084	0.87746	0.90838

Analysis of Variance for Sound Absorption Coefficient (SAC) and Noise Reduction Coefficient (NRC)

Next, all Sound Absorption Coefficient (SAC) and Noise Reduction Coefficient (NRC) results of 96 reprocessed samples were analyzed statistically by using the same tools, ANOVA. Firstly, the hypothesis test started with a test of main factors; H 0 and H 1 represented the main factors having no effect and having effects on the NRCs, respectively. Then, a test of interaction factors was carried on; H 0 and H 1 represented the interaction factors having no effect and having effects on the NRCs, respectively. All ANOVA results for the Noise Reduction Coefficients (NRCs) are indicated on Table 9. Statistical testers; F–Value or $F_0 > F_{0.05,(1,64)}$ was higher than 4.08 or P–Value was less than the significance level (α) of 0.05. The H 0 was rejected and the H 1 was accepted, the main and interaction factors had effects on the thermal conductivity of the reprocessed samples at the significance level (α) of 0.05 as following;
1) The main factor; B or density (kg/m^3), and
2) The main factor; D or thickness (mm).

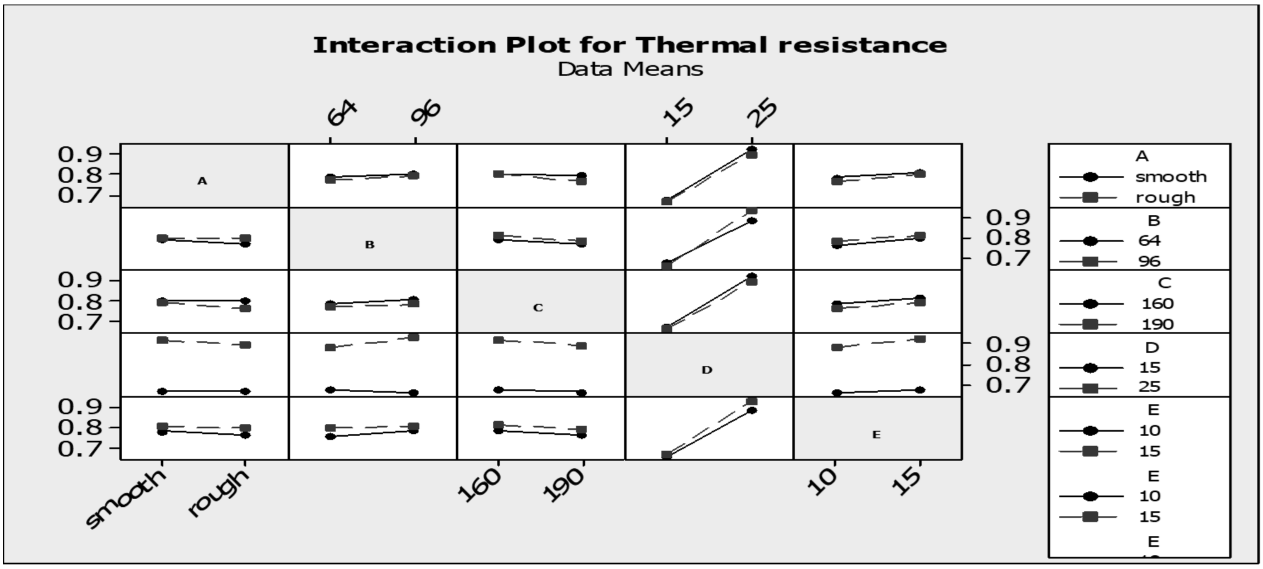


Figure 3. Interaction plots in the thermal resistance investigation

Then, Model Adequacy Checking was rendered to investigate suitability and accuracy of the information; error patterns followed the fundamental of $\varepsilon ij \sim N(0,\sigma 2)$ by using residual values. This analysis confirmed the accuracy and dependability of the information as shown on Figure 4. From the normal probability plot on Figure 5, the residual distribution was linear. The fitted value of each factor level distributed randomly and ordinarily around the center line, the residual distribution was not a megaphone pattern, this distribution implied that the data had the stability of their deviation and the data was independent. The residual distribution was not in any trends and patterns, the data were independent and not related to their collecting sequence.

Table 9. Analysis of Variance (ANOVA) results in the the Noise Reduction Coefficient (NRC) investigation

Source	df	SS	MS	F-valve (F0)	p-valve	Noted
A	1	0.00045	0.0045	1.05	0.315	
B	1	0.00477	0.00477	11.14	0.003	Sig.
C	1	0.000125	0.000125	0.29	0.593	
D	1	0.089860	0.089860	209.81	0.000	Sig.
E	1	0.000503	0.000503	1.18	0.288	
Error	64	0.011136	0.000428			
Total	95	0.106844				

S = 0.0206953 R-Sq = 89.58% R-Sq(adj) = 87.57%
Sig. = Significant

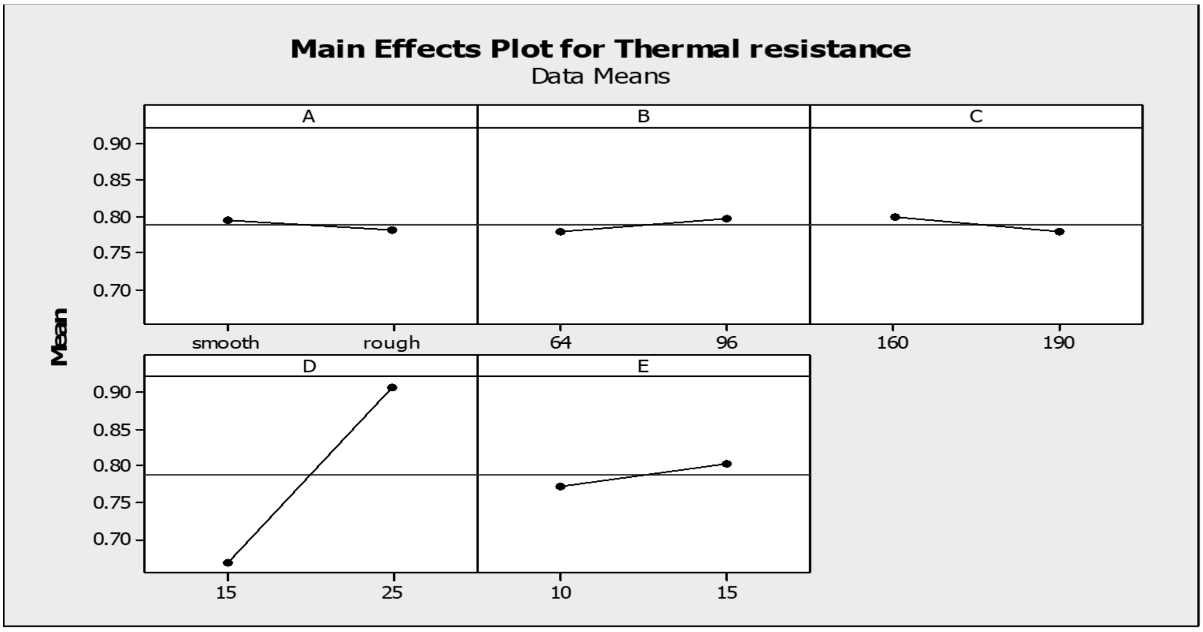


Figure 4. Main effect plots in the thermal resistance investigation

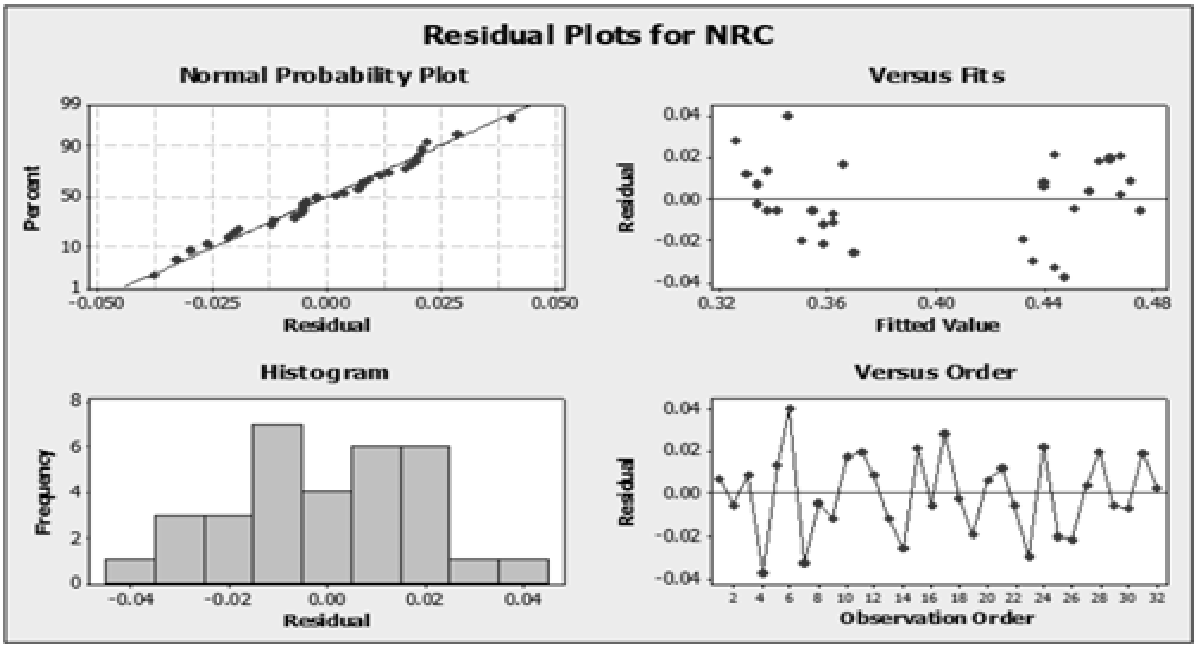


Figure 5. Residual plots in the Noise Reduction Coefficient (NRC) investigation

Finally, the analysis of the main factors was performed to find the suitable factor level. From Table 9, the mainactors; B and D, had effects on the NRCs. The effect of the main factors; B and D, on the NRCs was considered primarily as displayed on Figure 6. The highest NRC (good noise reduction) was indicated when the main factors; B or density was at 96 kg/m^3 and D or thickness was at 25 mm. Therefore, the suitable factors responding to the NRC and the hot press process were as following; the high level (+) of the factor; B or the density at 96 kg/m^3 and the high level (+) of the factor; D or the thickness at 25 mm. These factors could be used as the conditions of the reprocessing process and the highest average NRC was obtained from the 15th condition on Table 10 as 0.48881. Materials having NRCs above 0.4 can be considered as highly absorptive materials or acoustic, for an example, NRC values of materials used in offices and dwellings are in the range of 0.4 to 0.6 (Cowan, 1994). The acoustic property of the reprocessed sample related to the density and the thickness of the sample. Both surface roughness did not affect the NRCs notably,their NRCs were close, the average NRC of the rough surface sample. The Sound Absorption s mooth surface sample was a little bit higher than that of the rough surface sample. The Sound Absorption Coefficient or SAC varied in proportion to frequency levels; 125, 250, 500, 1,000, 2,000 and 4,000 Hz, respectively. NRC is the average of the SAC. Therefore, better acoustic materials have higher SACs as presented on Figures 7 and 8.

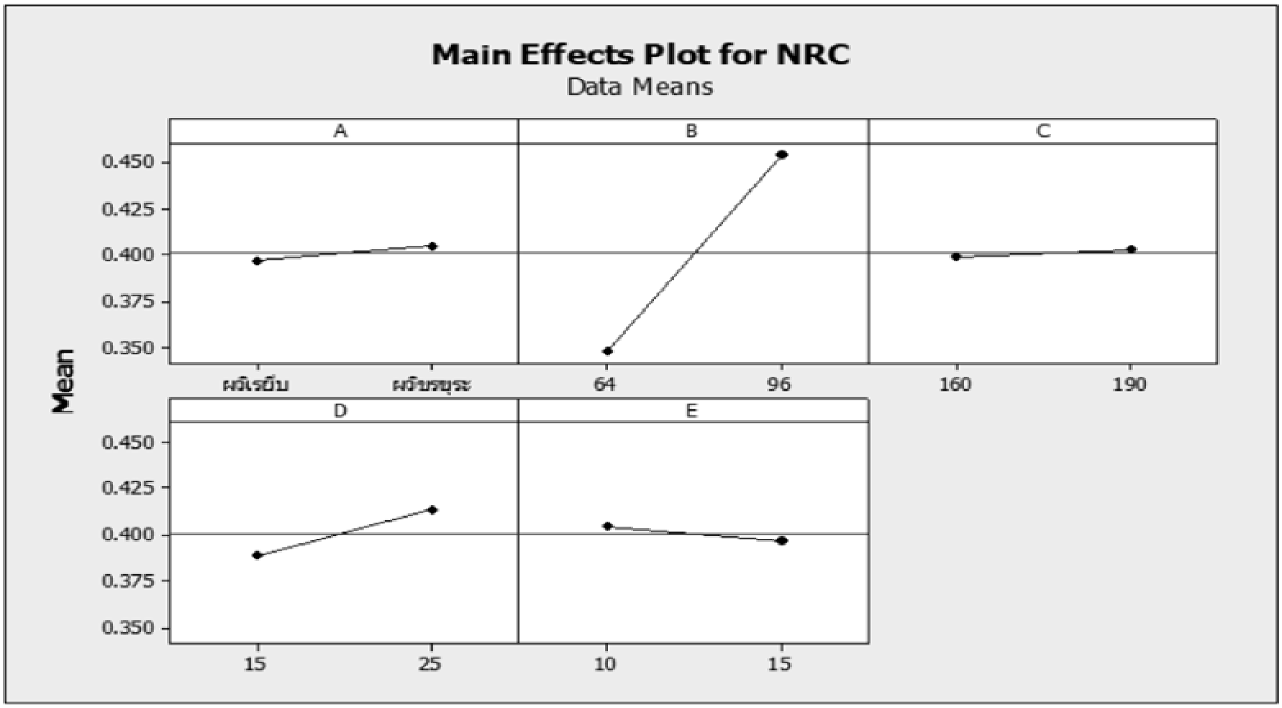
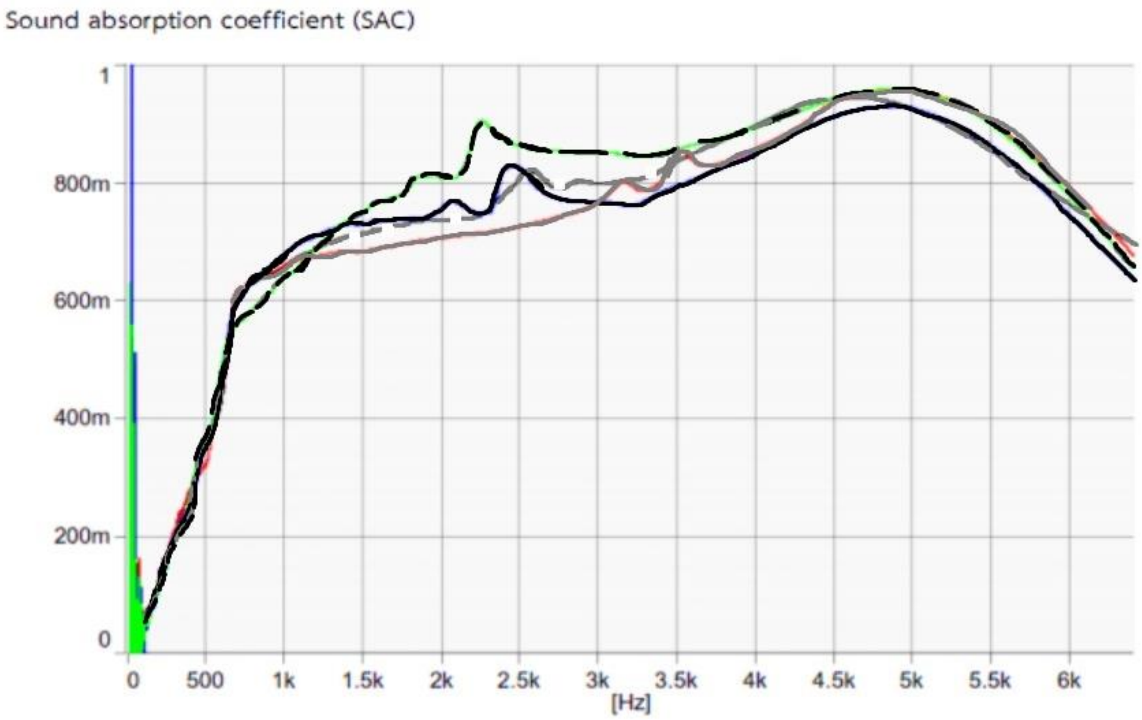
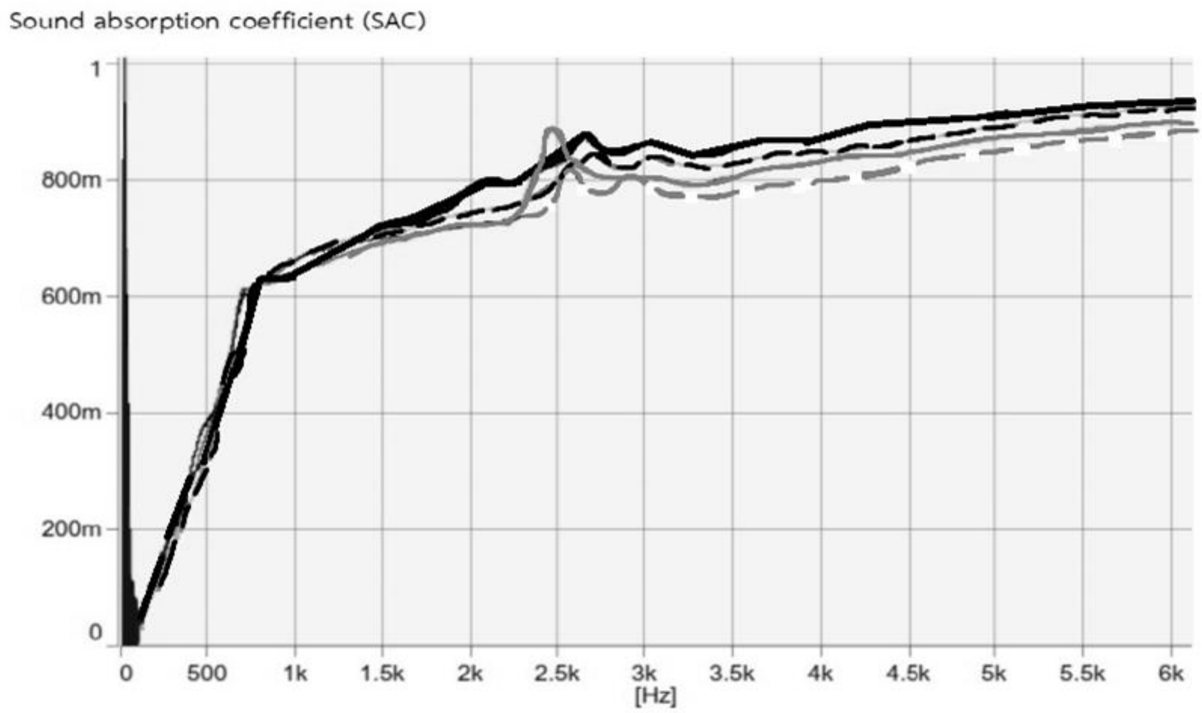


Figure 6. Main effect plots in the Noise Reduction Coefficient (NRC) investigation



Remark: Conditions; (black solid line) 96 g, 25 mm, 10 MPa, 160°C and smooth surface, (grey solid line) 96 g, 25 mm, 10 MPa, 160°C and rough surface, (black dash line) 96 g, 25 mm, 10 MPa, 190°C and smooth surface, (grey dash line) 96 g, 25 mm, 10 MPa, 190°C and rough surface.

Figure 7. Sound Absorption Coefficient (SAC) plots of the samples prepared at 10 MPa



Remark: Conditions; (black solid line) 96 g, 25 mm, 15 MPa, 160°C and smooth surface, (grey solid line) 96 g, 25 mm, 15 MPa, 160°C and rough surface, (black dash line) 96 g, 25 mm, 15 MPa, 190°C and smooth surface, (grey dash line) 96 g, 25 mm, 15 MPa, 190°C and rough surface.

Figure 8. Sound Absorption Coefficient (SAC) plots of the samples prepared at 15 MPa

The Cost Analysis and Product Comparison

Glass wool market survey was carried on to analyze and specify market feasibility of the reprocessed glass-wool board by using marketing mix or 4Ps; product, price, place and promotion. The product is an analysis and formulating strategy related to products or services. The price analyzes and determines the pricing strategy of the product from the customer's point of view, including comparisons with competitors. The place analyzes and defines shipping strategy, by adhering to the principles of efficiency, accuracy, safety and speed. The promotion is an analysis and formulating strategy that will boost the sales of the product. The information of the reprocessed glass wool board or the product is detailed on Table 11. The NRCs of different materials are compared on Table 12. The reprocessed board price was the same or a little lower than market prices. Since the reprocessed board was made from glass wool waste from vehicle industries, the reprocessed board properties were lower than the properties of the original glass wool boards. But the thermal resistance and NRC properties of the reprocessed board were well accepted. Board manufacturer interviews were conducted and expenses of the glass wool waste transportation and disposal had to be taken into the cost analysis, the cost tended to be lower than new glass wool boards in Thai markets. The certain cost could not be specified because this research was in the pilot plant stage.

Product distribution places could be divided into 2 ways; 1) the indirect-way in 2 levels (from manufacturers to wholesalers, retailers and customers, respectively, and 2) the direct-way from manufacturers to customers (customers may include absorptive manufacture industries and acoustic users). Since the reprocessed board can be considered as a waste-to-recycle product, promotional guidelines may emphasize acoustic users, green and recycle product users. This board can be raw materials for other acoustic composite boards. The reprocessed-board manufacturers may seek for commercial partners such as small acoustic businesses to develop the board quality and their own products or startup businesses. The startup businesses can make the reprocessed board widely known faster. Middleman promotions may play a role because they are professional, they know markets and customers trust their new product offers. If the reprocessed board is used as the raw material in the insulator and acoustic industries, the manufacturers fully develop their products by increasing the reprocessed board qualities and properties to meet their product standards and goals. The thermal resistances of three different boards were compared as shown on Table 13. These three boards were not covered with any layers. The first board was the reprocessed board from this work, the second was the board waste or the reprocessing raw material and the last board was the commercial insulation board. The lowest density was provided by the new commercial one while the reprocessing one provided the higher thermal resistance; 20.69% higher. As compared on the table, the reprocessed board could provide the competitive thermal resistance.

Table 10. Conditions providing the high Sound Absorption Coefficients of the reprocessed insulators

Codition	Factors					Noise Reduction Coefficient
	A	B	C	D	E	
7	Smooth	96	160	25	10	0.48331
8	Smooth	96	160	25	15	0.48071
15	Smooth	96	190	25	15	0.48881
16	Smooth	96	190	25	15	0.47035
23	Rough	96	160	25	15	0.46025
24	Rough	96	160	25	15	0.48424
31	Rough	96	190	25	10	0.47905
32	Rough	96	190	25	15	0.47035

Table 11. Prices of the sound absorbing materials in Thai market

Product Name	Size (MxM)	NRC	Price
acoustic wall panels CYLENCE ZofTone	0.60 × 0.60 0.60 × 1.20	0.69 – 0.98	240 – 440 Bath per Sheet
acoustic ceiling CYLENCE Wondary	0.60 × 0.60	0.70	655 – 754 Bath per m³
acoustic decorative wall CYLENCE Zandera	0.60 × 0.60 0.60 × 1.20	0.75	645 – 1715 Bath per Sheet
Reprocessed insulator (from Glass wool waste)	0.175× 0.175	0.46 – 0.49	N/A*

* No selling price for a prototype product

Table 12. Sound Absorption Coefficients of General Building Materials (Owens Corning, 2004)

Materials	Frequency (Hz)					NRC
	250	500	1000	2000	4000	
Brick	0.03	0.03	0.04	0.05	0.07	0.05
Carpet	0.05	0.10	0.20	0.30	0.40	0.15
Concrete Block	0.44	0.31	0.29	0.29	0.25	0.35
Fabrics	0.04	0.11	0.17	0.24	0.35	0.15
Glass	0.03	0.02	0.02	0.03	0.02	0.05
Gypsum Board	0.08	0.05	0.03	0.03	0.03	0.05
Hardwood	0.22	0.07	0.04	0.03	0.07	0.10
Reprocessed insulator (from Glass wool waste)	0.15	0.35	0.63	0.80	0.48	0.48

Table 13. Thermal resistance values of three samples; the reprocessed board (1), the board waste (2) and the commercial insulation board (3)

Numbers	Thickness	Density	R (m^2 W/m)
1	25	96	0.9879
2	37	64	0.0630
3	25	48	0.7810

Since the pressure, density and thickness of the reprocessed board were the interaction factors playing important roles on the board thermal resistance and Noise Reduction Coefficient (NRC) while both board surfaces; smooth and rough, were not significant, the thermal resistance and NRC correlations were proposed according to the significant factors as following;

$$R = 0.158 + (0.00359\ \text{Density}) + (0.0368\ \text{Thickness}) - (0.00267\ \text{Pressure}) + (0.00022\ \text{Density} \times \text{Thickness}) \quad (2)$$

$$NRC = 0.3258 + (0.000563\ \text{Density}) + (0.00855\ \text{Thickness}) + (0.00150\ \text{Pressure}) + (0.000137\ \text{Density} \times \text{Thickness}) \quad (3)$$

The correlations are applicable for the range of the reprocessed-insulator density, thickness and compression pressure from 64 to 96 kg/m^3, from 15 to 25 mm and from 10 to 15 bar, respectively. These correlations can help the manufacturers and users to predict the thermal resistances and Noise Reduction Coefficients of the recycled insulators in the forms of the significant factors. The manufacturers and users can also select these properties according to their desired thermal resistance and Noise Reduction Coefficient values.

CONCLUSION

Vehicle industries have to set budget to transport and dispose insulator waste from vehicle assembly processes. Glass wool is about 85% to 95% of the insulator waste; the main component of the insulator waste. This component, glass wool waste, was focused in this research as a raw material for the reprocessed insulator. A target insulator must provide thermal conductivity less than 0.031 W/m K and Noise Reduction Coefficient (NRC) more than 0.4. Analysis of Variance (ANOVA) was applied to find factors which responded to thermal resistances (R) and NRCs of the reprocessed specimens. Two levels of five factors were analyzed by ANOVA full factorial method. Five factors combined of reprocessing temperatures and pressures, density, thickness, and surface roughness values of reprocessed insulators. The total of 96 final reprocessed specimens were evaluated for their thermal resistances and NRCs. The analysis showed that density and thickness played an important role to the thermal resistance and NRC, the highest thermal resistance was 0.98028 m^2 K/W and the highest NRC was 0.48881. The R and NRC satisfied with the insulator properties. These factors were investigated from the reprocessing process in 0.2 m width and 0.2 m length molds. Results of this current research are applicable and useful in fabricating the reprocessed waste boards which can be used in building works. The reprocessed boards provide the same NRC as that of an open cell foam board. Moreover, the reprocessed boards could absorb noise better than concrete, wood and glass. The reprocessed boards are good insulators made from waste. However, the glass-wool-waste insulator have to be developed for better

NRC and thermal resistance properties. The insulator manufacturers that aim to reduce glass wool waste and desire to add values to the waste can take advantages from the research results. The reprocessed insulator can be considered as the better product for the better life quality in the sustainable society of our world.

ACKNOWLEDGEMENTS

This research was supported in part by the Graduate Program Scholarship from The Graduate School, Kasetsart University. This research was also financially supported by the Office of the Ministry of Higher Education, Science, Research and Innovation; and the Thailand Science Research and Innovation through the Kasetsart University Reinventing University Program 2021, as well as the research funding supported by Faculty of Science and Engineering, Kasetsart University, Chalermphrakiat Sakon Nakhon Province Campus.

REFERENCES

Ayuttaya P., 2007, *Design and Analysis of Experiments,* TOP Publishing Company, Bangkok, Thailand.

Choowonglert M. and Takkanon P., 2015, Sound Absorbing Sheets from Used Paper in the Office, *Proc. of 53th Kasetsart University Annual Conference*, Bangkok, 625-631.

Cowan J., 1994, *Handbook of Environmental Acoustics,* Van Nostrand Reinhold, New York, USA.

Homaswin K., Sangsupata S. and Intrachooto S., 2007, Para-Rubber and Coconut Fiber Integrated Acoustic Panels, *Proc. of 45th Kasetsart University Annual Conference*, Bangkok, 235-244.

Jeon C., Lee J., Chung H., Kim J. and Park J., 2017, A Study on Insulation Characteristics of Glass Wool and Mineral Wool Coated with a Polysiloxane Agent, *Advance in Meterials Science and Engineering,* 2017(3938965), 1-6.

Narakaew P. and Narakaew S., 2015, *The Efficiency of the Wall for Noise and Smell Adsorptions from Rice Straw Blended with Corncob Based Activated Carbon,* Research Report, Lampang Rajabhat University, Lampang, Thailand.

Owens Corning™, 2004, *Noise Control Design Guide*, United Artists Corporate, Ohio, USA.

Pakunworakij T., Puthipiroj P., Oonjittichai W. and Tisavipat P., 2006, Thermal Resistance Efficiency of Building Insulation Material from Agricultural Waste, *Journal of Architectural/Planning Research and Studies,* 4, 3-13.

Wajima T. and Matsuka S., 2019, A New Recycling Process of Waste Glass Wool Using Pyrolysis with Sodium Hydroxide, *International Journal of Chemical Engineering and Applications*, 10(3), 75-79.

Yodkaew R., Sangsupata S. and Intrachooto S., 2007, Sound Absorption of an Interior Ceiling Material from Chaff, *Proc. of 44th Kasetsart University Annual Conference*, Bangkok, 217-225.

Zhao C., Liu Y., Ren S. and Zhang Y., 2018, Life Cycle Assessment of Typical Glass Wool Production in China, *Materials Science Forum,* 913, 998-1003.