섬유질 단열재의 열적 특성 및 내화성능

Thermal Property and Fire Resistance of Cellulose Insulation

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Abstract

Cellulose insulation is primarily manufactured from recycled newsprint and treated with fire retardants for the fire resistance. Thanks to the fire retardants, it is not combustible and flammable. In addition to that, Its thermal resistance is much better than that of fiberglass or rock wool. It is made from waste paper and easily decayed when it is demolished, and it has small embodied energy. So it is very environment-friendly building material. For broader use of cellulose insulation in buildings in Korea, it is necessary to test its physical performance to compare the results with the requirements on the Korean Building Code. To this end, apparent thermal conductivity (ka) measurements of Korean-made loose-fill cellulose insulations were recently completed using equipment that was built and operated in accordance with ASTM C 518 and the fire resistance was tested in accordance with ASTM C 1485. Korean loose-fill cellulose has thermal conductivity about 5% greater than the corresponding U.S. product at the same density. This is likely due to differences in the recycled material being used. Both spray-applied and loose-fill cellulose insulation lose about 1.5% of their thermal resistivity for 5.5°C increase in temperature. The fire resistance of cellulose insulation is increased in linear proportion to the increase of the rate of fire retardant. Thanks to the high fire resistance, cellulose insulation can be used as a substitution of Styrofoam or Urethane foam which is combustible. The thermal conductivity of cellulose insulation was 0.037-0.043W/m·K at the mean specimen temperature from 4-43°C. It corresponds to the thermal resistance of "Na Grade" according to the Korean Building Code. The effect of chemical content on thermal conductivity was negligible for all but the chemical-free specimen which had the highest value for the thermal conductivity over the temperature range tested. The thermal resistance of cellulose insulation is better than that of fiberglass or rock wool, and its fire resistance is higher than that of Styrofoam or Urethane foam. Therefore it can be substituted for those above considering its physical performance. Cellulose insulation is no more expensive than Styrofoam or rock wool, so it is recommended to use it more widely in Korea.

요 지

섬유질 단열재는 주로 폐신문지로 만드는 데, 내화성능을 위해 내화재로 처리된다. 내화재로 인해 연소가 되지 않을 뿐 아니라, 연기도 나지 않는다. 섬유질 단열재의 열저항은 유리섬유나 암면보다 더 뛰어나다. 섬유질 단열재는 폐지로 만들어지므로 폐기시에는 잘 부식되고, 내재에너지 또한 매우 작은 친환경 단열재이다. 국내 건축물에 섬유질 단열재를 광범위하게 이용하기 위해서는 국내 건축법규 상의 단열규정에 적합한지 여부를 판단할 수 있는 물리적 성능 테스트가 필요하다. 따라서 국내에서 생산되는 섬유질 단열재에 대한 열전도율 및 내화성능 실험을 ASTM C 518과 ASTM C 1485에 근거하여 실시하였다. 국내생산 섬유질 단열재는 동일밀도의 미국제품에 비해 열전도율이 약 5%정도 높게 나타났다. 이러한 결과는 폐지원지의 섬유질이 서로 다른데서 기인하는 것으로 판단된다. 습식분사방식과 공기충진방식 모두 온도가 5.5°C 상승할 때 마다 약 1.5%씩 열전도율이 높아지는 것으로 나타났다. 섬유질 단열재의 내화성능은 내화재의 함유량에 비례하여 일정하게 증가되는 것으로 나타났다. 높은 내화성능으로 인해 불에 약한 우레탄폼이나 스치로폼을 대체할 수 있다. 섬유질 단열재의 열전도율은 시편의 온도가 4-43°C인 경우 0.037-0.043W/m·K로 나타났다. 이는 국내 건축법규 상의 "나"등급에 해당하는 값이다. 내화재가 열전도율에 미치는 영향은 미미하였으며, 내화재가 전혀 들어있지 않은 경우가 가장 열전도율이 높게 나타났다. 섬유질 단열재의 단열성능은 유리섬유나 암면에 비해 뛰어나고, 스치로폼이나 우레탄폼에 비해 내화성능은 훨씬 뛰어나다. 따라서, 물리적인 성능을 고려한다면 위의 기존 단열재들을 대체할 수 있다. 섬유질 단열재는 스치로폼이나 우레탄폼에 비해 값도 싸므로 국내에서도 더욱 폭 넓게 사용하는 것이 추천된다.

Keywords : Cellulose, Insulation, Thermal Conductivity, Fire Resistance

핵심 용어 : 섬유질, 단열재, 열전도율, 내화성능

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?본 논문에 대한 토의를 2005년 9월 30일까지 학회로 보내주시면 2006년 1월호에 토론결과를 게재하겠습니다.

1. Introduction

Cellulose insulation for use in building applications is primarily manufactured from recycled newsprint or cardboard using shredders and fiberizers. Cellulose insulation as a product is about 80 wt.% cellulosic fiber and 20 wt.% chemicals, most of which are fire retardants such as boric acid and ammonium sulfate.(1) Thanks to the fire retardants, it is not combustible and flammable. In addition to that, Its thermal resistance is much better than that of fiberglass or rock wool. Considering its environment-friendly characteristics, it is recommendable to be much used in buildings in Korea. The cellulose industry in Korea is in an early stage of development with current production of about 1000 tons a year.(2) Its current market share as building insulation is only about 0.3%. Organic insulations such as polystyrene foam board and polyurethane foam occupy about 71% of the total Korean insulation market, and inorganic insulations such as fiberglass and rock wool make up about 29%.(3) On the other hand, in North America, About 750,000 tons of paper has been recycled as cellulose insulation annually for the past two years in the U.S. That would imply a production volume of about 940,000 tons of cellulose insulation per year. The market share for cellulose insulation in residential buildings is 8-10 % and it claims 20-25% in the commercial spray-insulation market.(4) Cellulose insulation in the U.S. generally conforms to one of three ASTM Standard Specifications. ASTM C 739(5) is the Standard Specification for loose-fill cellulose insulation commonly used in attics or similar horizontal applications. ASTM C 1497(6) is the Standard Specification for stabilized cellulose generally intended for horizontal applications. Stabilized cellulose is made by adding an adhesive to loose-fill insulation to reduce post-installation settling. Self-supported spray-applied cellulose insulation described in the ASTM C 1149(7) is commonly used in commercial applications. Spray-applied cellulose insulation contains a significant amount of adhesive that permits it to be installed on walls and ceilings without support.

A typical cellulose manufacturing plant includes facilities for storing and moving large quantities of waste paper, chopping and shredding, milling or fiberizing, adding chemicals, and packaging. Figure 1 shows the flow of paper and chemicals through a fiberizer plant.1) The manufacturing process being described involves the mixing of fiberized paper and chemical additions to form a product that is packaged in bags or bales for shipment. While both Korean and U.S. cellulose insulation is produced by the same fiberizing processes, the feed stocks in the two countries are different. Korean newspaper is usually made of paper that has been recycled many times with the result that Korean cellulose insulation has shorter fibers and is more brittle than the corresponding U.S. product.(2)

For broader use of cellulose insulation in buildings in Korea, it is necessary to test its physical performance and to compare the results with the requirements on the Korean Building Code. To this end, the effect of density and temperature on the thermal conductivity of loose-fill cellulose insulation manufactured in Korea and U.S. was recently reported.(8) The apparent thermal conductivity of a particular type of spray-applied cellulose insulation was also determined and compared with previously published data.(9) In addition to that, the thermal conductivity and the fire resistance of Korean-made cellulose containing different amounts of chemical fire retardant

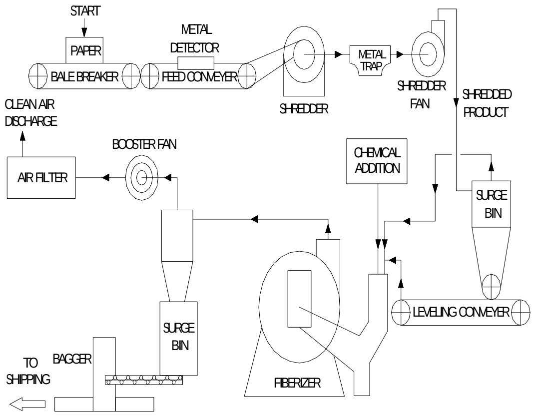

Fig. 1 Flow Process for the Manufacture of Cellulose Insulation

were investigated.

2. Fire Resistance Test of Cellulose Insulation

2.1 Preparation of Specimen

In Korea, Russian boric acid has been used as a fire retardant for cellulose insulation. Fire retardant triturator was controllable to fit its amount from 10 to 300rpm. In the factory, the fire retardant was inputted at the rate of 130rpm, and the recycled paper was inputted at the constant rate of 28.8kg/min. To verify the rate of the fire retardant in the product, the rpm of the triturator was set as 60, 70, 80, 90, 100, 150, 200rpm, and each weight of the inputted fire retardant for a minute was averaged from three times measurements.

As a result, based on the inputted rate of fire retardant a minute at each rpm and that of recycled paper, the rate of fire retardant was

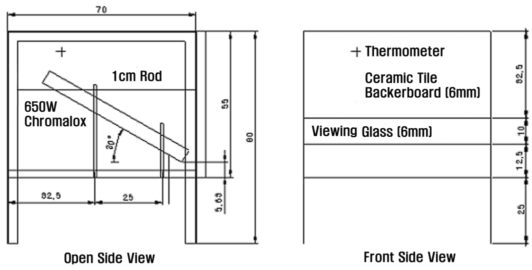

Fig. 2 Drawing of Test Chamber

Table 1 Rate of fire retardant according to the inputted speed

Inputted Speed (rpm)	Boric Acid (kg/m)	Recycled Paper(kg/m)	Rate of Fire Retardant (%)
60	1.464	28.8	4.8%
70	1.867	28.8	6.1%
80	2.327	28.8	7.5%
90	2.727	28.8	8.6%
100	3.157	28.8	9.9%
150	5.157	28.8	15.2%
200	7.237	28.8	20.1%

calculated.

According to the table 1, the rate of fire retardant was about 4.8% and 13% at 60rpm and 130rpm, which shows linear relation. To test the fire resistance according to the rate of the fire retardant, 8 kinds of sample were produced from 5% to 22.5% with the interval of 2.5%.

There are several test methods such as ASTM C-739, ASTM C 1485-00, and Veri-Flux "100" used for fire resistance of cellulose insulation. All these methods require test chambers. The method of ASTM C 1485-00 was used in this study. This test method covers a procedure for measuring the critical radiant flux of exposed attic floor insulation subjected to a flaming ignition source in a graded radiant heat energy environment inside a test chamber. The test specimen can be any attic floor insulation.

This test method is not applicable to those insulations that melt or shrink away when exposed to the radiant heat energy environment or ignition source.(15)

The drawing and the appearance of test chamber are Figure 2 and 3. Figure 4 shows a data logger to test critical radiant flux.

From the test result of radiant flux from the dummy specimen calibration board, calibration curve was achieved. The dimension of the dummy specimen calibration board is 5×60×15cm. It is composed of cement board having 2.5cm diameter drilled holes at intervals of 10cm. The radiant flux from the heat element was measured using Heat Flow Sensor MF-140 of Japanese EKO INSTRUMENTS.

Calibration curve is used for the determination of the critical radiant flux based on the three burn distances in a test chamber. The achieved calibration curve was Figure 5. Samples were conditioned to equilibrium at 21±2°C and 50±5% relative humidity in an open-top mesh bottom container not exceeding 10.0cm in depth and position in such a way to allow free movement of air on the exposed sides. The specimen should be taken to the testing area and allowed to stabilize for 10 min to room temperature.

2.2 Fire Resistance Test Results

Figure 6 shows the specimen is burning and Figure 7 shows the scene measuring the burn length.

Figure 8 shows the combustion length and critical radiant flux according to the rate of the fire retardant. The results indicate that the rate of the fire retardant is about 18% to satisfy the critical radiant flux of 0.12W/cm² and over.

Fig. 3 Test Chamber

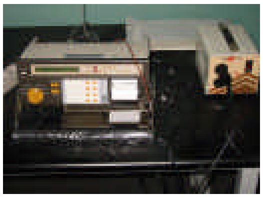

Fig. 4 DATA Logger

Fig. 6 Burning Process

Fig. 7 Measuring Burn Length

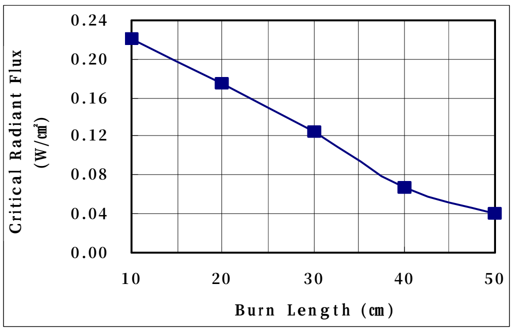

Fig. 5 Calibration curve

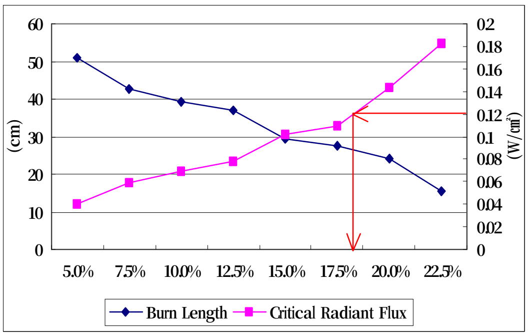

Fig. 8. Combustion Length and Critical Radiant Flux of Cellulose Insulation according to the Rate of Fire Retardant

3. Thermal Test Results and Correlations

3.1 Preparation of Specimen

The labeled density of Korean loose-fill cellulose insulation was surveyed and found to be in the range of 25 to 30 kg/m^3. On the other hand, a survey of six major U.S. cellulose insulation manufacturers indicates loose-fill cellulose insulations are currently labeled in the density range of 23.5 to 27.0 kg/m^3 for attic products.

Apparent thermal conductivity (k_a) measurements of Korean-made loose-fill cellulose insulations were recently completed using equipment that was built and operated in accordance with ASTM C 518.[10]

The commercially-built heat-flow meter was calibrated using high-density fiberous glass board, SRM 1450b.[11] The heat-flow meter measurements were made using 30.5×30.5cm specimens at thickness varying from 2.5 to 10cm. The mean test specimen temperature include 4°C, 10°C, 24°C, 38°C, 43°C designated in ASTM C 1058-97 : Selecting temperatures for evaluating and reporting thermal properties of thermal insulation,[12] and 17°C and 31°C were added to get a constant interval. The test specimens were conditioned in a laboratory environment of 21±1°C and 50±5%RH for at least 24 hours and the change of the weight was within 1% before any tests were performed. Test data were also collected for a new type of spray-applied cellulose insulation (SACI) and compared with previously published data.[13],[14]

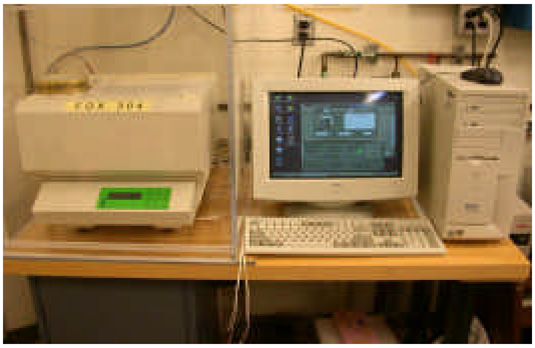

Fig. 9 Thermal Conductivity Testing Apparatus

The new type of SACI is made with a foamable adhesive and has densities in the range of 47.8 to 79.1 kg/m^3.

3.2 Thermal Conductivity Test Results

Cellulose insulation material in the US is labeled with properties measured at a mean temperature of 24℃(75℉). Korean products are usually labeled at 20℃. However, for the purpose of comparison, the thermal properties at 24℃ were used in this paper. The test specimens of US and Korean cellulose used for comparison were not chemically treated. The specimens were hand-loaded to achieve specific densities. Based on these measurements, the apparent thermal conductivity (k_a, W/m·K) as a function of temperature is given by Eq. (1) for Korean cellulose and Eq. (2) for US cellulose both at a density of 25.5 kg/m^3.

$$k_{a\ Korean} = 0.0365+0.000146T \quad (1)$$

$$k_{a\ US} = 0.0346+0.000138T \quad (2)$$

These two equations were obtained from previously reported data.[8] The value for k_a at 24°C for Korean-made cellulose at 25.5kg/m^3 is 0.0400W/m·K while the corresponding k_a for US-made cellulose is 0.0379 W/m·K.

The difference in k_a between the two products is about 5%. The temperature coefficient, dk_a/dT, is 0.000146 $W/m \cdot K^2$ for Korean cellulose and 0.000138 $W/m \cdot K^2$ for U.S. cellulose. Data obtained by Tye showed dk_a/dT value of 0.000220 $W/m \cdot K^2$ at 24.0kg/m^3 and also 0.000136 $W/m \cdot K^2$ at 32.0kg/m^3.[16] The insulation from both sources gain about 2% of their thermal conductivity for each 5.5℃ increase in temperature. The corresponding number for dry air is 1.6%.[17] The results for k_a as a function of temperature of Korean and U.S. cellulose of the same density are shown in Table 2. The result shows that the k_a of Korean cellulose insulation is about 5% greater than the corresponding U.S. product.

The Eq. (1) for Korean cellulose insulation gives k_a of 0.0394W/$m \cdot K$ and an R-value per mm of thickness of 0.0254 $m^2 \cdot K/W$ at 20°C. This product, consequently, will provide thermal resistances of R-5.28, R-7.04, and R-8.81 when installed in typical attic applications of 20.8 cm, 27.7 cm and 34.7 cm of insulation.

Table 3 shows the U-values in Korean Building Code.[18] The minimum thickness of an envelope in a certain area can be calculated using Eq. (3).

$$U=1/R=1/[(0.1075)+\sum(d/k_a)+(0.03448)] \quad (3)$$

Table 2 Thermal Conductivity of Korean and US Cellulose at 25.5kg/m^3

Mean Specimen Temperature (℃)	k_a ($W/m \cdot K$)		
	Korean (Eq. 1)	US (Eq. 2)	% Difference
4	0.0371	0.0352	5.2%
10	0.0379	0.0360	5.2%
17	0.0389	0.0369	5.2%
24	0.0400	0.0379	5.4%
31	0.0410	0.0388	5.3%
38	0.0420	0.0399	5.2%
43	0.0428	0.0406	5.2%

U: Thermal conductance ($W/m^2 \cdot K$)
R: Thermal resistance ($m^2 \cdot K/W$)
0.1075 & 0.03448 : Inside and outside surface resistances
d: Thickness of insulation (m)
k_a: Thermal conductivity ($W/m \cdot K$)

In case of an exterior wall in Seoul, which be-

Table 3 The U-values in Korean Building Code (Unit : $W/m^2 \cdot K$)

Area	Envelope Condition		Middle Area*	Southern Area**	Jeju Island
Exterior Wall of Living Room	Facing Outdoor Air directly		Less than 0.47	Less than 0.58	Less than 0.76
	Facing Outdoor Air indirectly		Less than 0.64	Less than 0.81	Less than 1.10
Upper-most Ceiling or Roof of Living Room	Facing Outdoor Air directly		Less than 0.29	Less than 0.35	Less than 0.41
	Facing Outdoor Air indirectly		Less than 0.41	Less than 0.52	Less than 0.58
Lower-most Floor of Living Room	Facing Outdoor Air directly	Floor-Heating	Less than 0.35	Less than 0.41	Less than 0.47
		Non Floor-Heating	Less than 0.41	Less than 0.47	Less than 0.52
	Facing Outdoor Air indirectly	Floor-Heating	Less than 0.52	Less than 0.58	Less than 0.64
		Non Floor-Heating	Less than 0.58	Less than 0.64	Less than 0.76
Sidewalls of Apartment House			Less than 0.35	Less than 0.47	Less than 0.58
Floor between Apartment Units	Floor-Heating		Less than 0.81	Less than 0.81	Less than 0.81
	Non Floor-Heating		Less than 1.16	Less than 1.16	Less than 1.16
Window and Door	Facing Outdoor Air directly		Less than 3.84	Less than 4.19	Less than 5.23
	Facing Outdoor Air indirectly		Less than 5.47	Less than 6.05	Less than 7.56

*Middle Area : Seoul, Incheon, Gyunggido, Gangwondo (except Gangneung, Donghae, Sokcho, Samchuk, Gosung, Yangyang), Chungchongbukdo (except Youngdong), Chungchongnamdo(Chunam), Gyungsangbukdo (Chungsong)
**Southern Area : Busan, Daegu, Gangju, Daejun, Gangwondo(Gangneung, Donghae, Sokcho, Samchuk, Gosung, Yangyang), Chungchongbukdo (Youngdong), Chungchongnamdo(except chunan), Jeonlabukdo,

longs to middle area, the minimum thickness (d) of 25.5kg/m^3 cellulose insulation by itself is 0.0782 m to satisfy the U-value requirement of 0.47W/m^2·K. If several envelope materials such as brick or gypsum board are added to the cellulose insulation, the minimum thickness of cellulose insulation can be reduced. Therefore its thermal performance is enough to be used as building insulation in Korea.

Cellulose insulation used in wall cavities in normally at a higher density than that used in attic applications. Table 3 contains some apparent thermal conductivity data recently reported for spray-applied cellulose produced with a foamable adhesive.[9] The current data are compared with previously published data in Figure 10.

Measured k_a values for spray-applied cellulose insulation at 24°C have been obtained for densities from 34.9 to 123.8kg/m^3 and they are marked as square.[14] Data points from Yarbrough et al.[13] are shown as diamonds and data from the present study are indicated by triangles. The k_a of spray-applied cellulose insulation measured in this project was 0.004 to 0.007 W/m·K above the data published in 1990.

Table 4 contains the test results for the spray-applied cellulose specimens. The units for

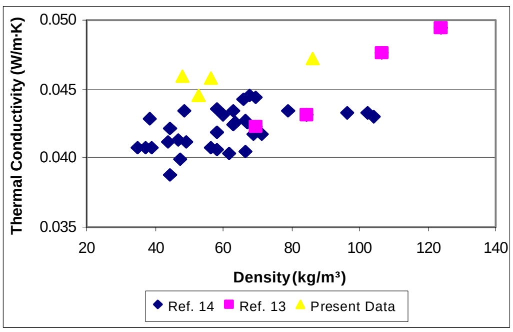

Fig. 10 A Comparison of k_a for Spray-Applied Cellulose from Three Sources

Jeonlamando, Gyungsangbukdo(except Chungsong), Gyungsangnamdo

thermal conductivity (k_a) are W/m·K and density ( ) is expressed as kg/m^3.

From the Table 3, the k_a of 47.8kg/m^3 is represented by Eq. (4).

$$k_{a\ SACI} = 0.04274+0.000142T \quad (4)$$

From the Eq. (4), the R-value at 20°C for a typical wall cavity installed with 47.8kg/m^3 spray-applied cellulose insulation would be R-1.1 at 5 cm, R-2.2 at 10 cm, and R-3.3 at 15 cm thick.

The 24°C thermal data in Table 2 was compared with corresponding loose-fill values in Figure 3. Spray-applied cellulose products containing adhesive have greater k_a than loose-fill products at the same density. The recently obtained data and previously reported data support this observation. The data in Figure. 11 show recently measured k_a for "Fiberiffic"[19] insulation made with cellulose and that for loose-fill cellulose published by McElroy et al.[20]

The spray-applied cellulose has on the average a k_a about 5% greater than the loose-fill insulation at the same density.

Table 4 Test Results for the Specimens of Spray-Applied Cellulose Insulation (SACI)

T-mean (℃)	k_a(W/m·K)			
	47.8kg/m^3	50.6kg/m^3	55.4kg/m^3	79.1kg/m^3
4	0.0429	0.0417	0.0431	0.0453
10	0.0437	0.0425	0.0439	0.0460
17	0.0448	0.0434	0.0448	0.0468
24	0.0459	0.0445	0.0458	0.0472
31	0.0468	0.0453	0.0465	0.0475
38	0.0477	0.0461	0.0472	0.0479

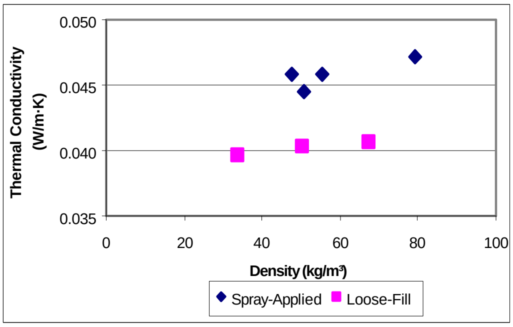

Fig. 11 A Comparison of ka for Spray-Applied Cellulose Insulation with Loose-Fill Insulation

The spray-applied insulation, however, is less likely to settle with time.

4. Variation of Apparent Thermal Conductivity with Temperature

Figures 12 shows the variation of thermal conductivities of the spray-applied cellulose insulation with temperature in the range of 4-43°C.

The temperature coefficient, dk_a/dT is 0.000129 for SACI at a density of 55.4kg/m³. Data obtained by Yarbrough for SACI showed dk_a/dT values of 0.000061 at 62.9kg/m³ and 0.000084 at 68.0kg/m³.[14] The insulation gains about 1.5% of their thermal conductivity for each 5.5°C increase in temperature. The thermal conductivities of the

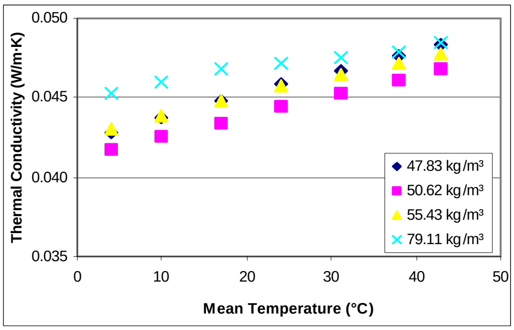

Fig. 12 Thermal Conductivity of Spray-Applied Cellulose Insulation

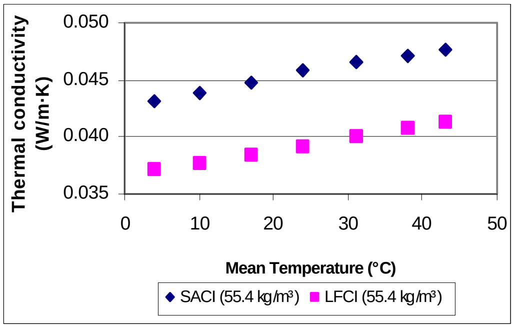

Fig. 13 Apparent Thermal Conductivity of SACI and LFCI

Table 5 Thermal conductivity of SACI(=55.4 kg/m³) and LFCI(=55.4 kg/m³)

Mean Specimen Temperature(°F)	Thermal Conductivity(W/m·K)		
	SACI	LFCI	%Difference
4	0.0431	0.0372	13.8%
10	0.0439	0.0378	13.9%
17	0.0448	0.0385	14.1%
24	0.0458	0.0392	14.3%
31	0.0465	0.0400	13.9%
38	0.0472	0.0408	13.5%
43	0.0477	0.0413	13.4%

$k_{a\ SACI}$ = 0.0427+0.000129T
$k_{a\ LFCI}$ = 0.0367+0.000104T

SACI and the LFCI are compared in Table 5 and Figure 13. The specimen was hand-loaded to achieve the density of 55.4 kg/m³.

Table 5 and Figure 13 show a comparison of the thermal conductivity of SACI and LFCI over the temperature range of 4 to 43°C. The difference between the two types of insulation averages about 14%.

5. Conclusions

The results of this study can be summarized as follows.

1) Korean loose-fill cellulose has k_a about 5%

greater than the corresponding U.S. product at the same density. This is likely due to differences in the recycled material being used.

2) Spray-applied cellulose yields R-value in the range of R-1.1 to R-3.3 at 20°C and thickness of 5cm to 15cm. These values are based on a density of 47.8 kg/m^3.

3) A new type of foamable spray-applied cellulose has k_a slightly higher than previously tested spray-applied cellulose.

4) Both spray-applied and loose-fill cellulose insulation lose about 1.5% of their thermal resistivity for 5.5°C increase in temperature.

5) The thermal conductivity of cellulose insulation showed linear increase with the increase of the mean temperature of specimens.

6) The thermal conductivity of cellulose insulation was 0.037-0.043W/m·K at the mean specimen temperature from 4-43°C. It corresponds to the thermal resistance of "Na Grade" according to the Korean Building Code.

7) The effect of chemical content on thermal conductivity was negligible for all but the chemical-free specimen which had the highest value for the thermal conductivity over the temperature range tested.

8) The fire resistance of cellulose insulation is increased in linear proportion to the increase of the rate of fire retardant. Thanks to the high fire resistance, cellulose insulation can be used as a substitution of Styrofoam or Urethane foam which is combustible.

9) Boric acid is used as fire retardant for Korean cellulose insulation, the equivalent rate of which for the critical radiant flux of 0.12W/cm^2 was 18%, which satisfies the US fire resistance guideline.

10) The thermal resistance of cellulose insulation is better than that of fiberglass or rock wool, and its fire resistance is higher than that of Styrofoam or Urethane foam. Therefore it can be substituted for those above considering its physical performance.

11) Cellulose insulation is no more expensive than Styrofoam or rock wool, so it is recommended to use it more widely in Korea.

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(접수일자 : 2005년 4월 29일)