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Comparative Study on Life Cycle Assessment for Typical Building Thermal Insulation Materials in China

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Abstract. Studies on life cycle assessment of three typical building thermal insulation materials including polystyrene board, rock wool board, and rigid foam polyurethane board related to building energy-saving were carried out. Based on the method of life cycle assessment, "1 kg of thermal insulation material" is first selected as one of the functional units in this study based on the production field data statistics and general market transaction rules of the thermal insulation materials, and life cycle resource consumption, energy consumption and exhaust emission of the three products in China are deeply surveyed and analyzed. The abiotic depletion potential (ADP), primary energy demand (PED), and global warming potential (GWP) for production of 1 kg of the three thermal insulation materials are calculated and analyzed. Furthermore, the functional unit is extended to be "1 m^2 of thermal insulation material meeting the same energy-saving requirements" so as to compare the difference of environmental friendliness among the three building thermal insulation materials, and the corresponding life cycle environmental impact is also calculated and analyzed. As shown by the results, where calculated in unit mass, the order of production life cycle environmental impact significances of the thermal insulation materials is as follows: rock wool board < polyurethane board < polystyrene board. However, where calculated in unit area (m^2) meeting the 65% energy-saving requirements, the production life cycle environmental impact significances of the three kinds of insulation materials are sorted as polystyrene board < polyurethane board < rock wool board, whatever the region is, which is opposite with that of the results for the insulation materials in unit mass (kg). The reason for such difference is that they have different volume weights and heat conductivity coefficients. The polystyrene board has a smaller volume weight and the smallest heat conductivity coefficient, whereas the rock wool board has the highest volume weight and heat conductivity coefficient.
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Introduction

As the policies for building energy efficiency has been fully implemented and the green building action widely carried out, the technology for the assessing and verifying green building materials is vital and needs to be established as soon as possible. Thermal insulation materials directly affect the building energy efficiency, so the studies on their green degree assessment and verification are pressing and of practical significance. Moreover, the Ministry of Industry and Information Technology has included the building external thermal insulation materials into the major objects of green building material product standardization so as to coordinate with the green building action.

Life cycle assessment (LCA) method is the one that quantitatively describes the consumption of various resources and energies as well as the emission of pollutant in the product life cycle and then assesses the product's environmental impact in a systematic way[1,2]. It was included into the ISO 14000 series of standards for environment management as an important tool, which is defined as the method basis for other ones specified in the serious, and has been widely employed in various fields including the assessment of product green degree, the ecological design[3], the assessment, research and development of cleaner production technology, the environmental labeling and declaration[4], and the development of environmental policy. Furthermore, the building material LCA analysis is increasingly taken into consideration regarding to the green building evaluation in both China and abroad[5-7]. Therefore, the study on life cycle assessment for thermal insulation materials is essential to the green degree assessment or even the green building evaluation.

At present, the study on life cycle assessment for thermal insulation materials [8,9] is rarely reported in China. This paper has performed the life cycle assessment on three most widely used thermal insulation materials (namely, the polystyrene board, the polyurethane board and rock wool board) in the current domestic building engineering based on the LCA method, combining the characteristics of the employing of such materials in different regions, and is aimed to illustrate the basic information of the life cycle environmental load of thermal insulation materials in this industry and to provide data support to the establishment of localized LCA database for thermal insulation materials and the assessment of green building materials.

Method for the Study

Determining the model for life cycle. According to ISO 14040 series of standards, the LCA methodological framework consists of the following four parts: (1) goal and scope definition, which specifies the determination of the goals, the system boundary, the functional unit, and etc; (2) life cycle inventory analysis (LCI), which specified that the data related to the energy consumption and emissions to air, discharges to water and soil in each unit process and stage within the product life cycle shall be determined, and classified under several major headings, and created an inventory; (3) life cycle impact assessment (LCIA), which describes the quantitive evaluation of the inventory data; (4) life cycle interpretation, where the results should be delivered, the conclusions reached, limitations explained and recommendations provided.

The life cycle of product can be summarized to three stages: (1) The upstream process, which includes the acquisition and production of resource, energy and raw materials, the production of product-packaging materials, and the transportation involved herein; (2) The production process, including the manufacturing of products and the treatment of the emissions in this stage; (3) The downstream process, which includes the production distribution, use, disposal and recycle. As for the non-end-use products, their life cycle assessment model generally covers only the upstream process and the production process, namely, from the "cradle" to the "gate". Therefore, as the upstream building products, thermal insulation materials are evaluated based on the fundamental model of "from the 'bassinet' to the 'gate' ", namely, they are subjected to the production life cycle assessment in this paper.

Determining the functional unit. The study in this paper has determined the following two functional units based on different goals:

1) "Production of 1 kg of insulation board" is firstly selected as one of the functional units in this study based on the production field data statistics and general market transaction rules of the thermal insulation materials.

2) The functional unit is extended to be the "production of 1 m^2 of insulation board meeting the same energy-saving requirements" so as to compare the difference of environmental friendliness in the life cycle between different thermal insulation materials.

Determining the impact assessment indicators. This study focuses on the abiotic depletion potential (ADP), the primary energy demand (PED), and the global warming potential (GWP) after comprehensively considering the limitation of LCA indicator model study and its application scope, the major concerns of the domestic and foreign policies, the characteristics of thermal insulation material production, and the direct correlation to green building evaluation etc.

Life Cycle Assessment for Production of Insulation Board in Unit Mass

Definition of goals. Select the polystyrene board, the rock wool board and the rigid foam polyurethane board as the objects and conduct the life cycle assessment for them adopting “the product production in unit mass” as the functional unit in the hope of providing data support to the establishment of localized LCA database for China thermal insulation material industry and to the green building evaluation.

Determining the system boundary. This study adopts the life cycle assessment model of "from the cradle to the gate" and the system boundary includes as following:

1) The manufacturing process of insulation boards (the process flow chart of each product can be seen in Fig. 1-3);

2) The life cycle stages involved in the raw materials production;

3) The production of electricity and energy;

4) Transportation of raw materials.

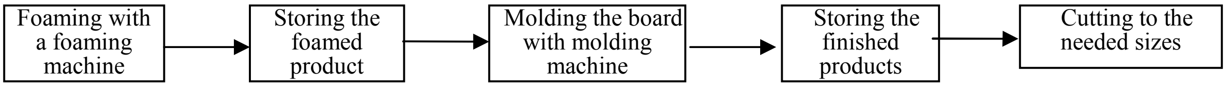

Fig. 1 Production technology flow of polystyrene board

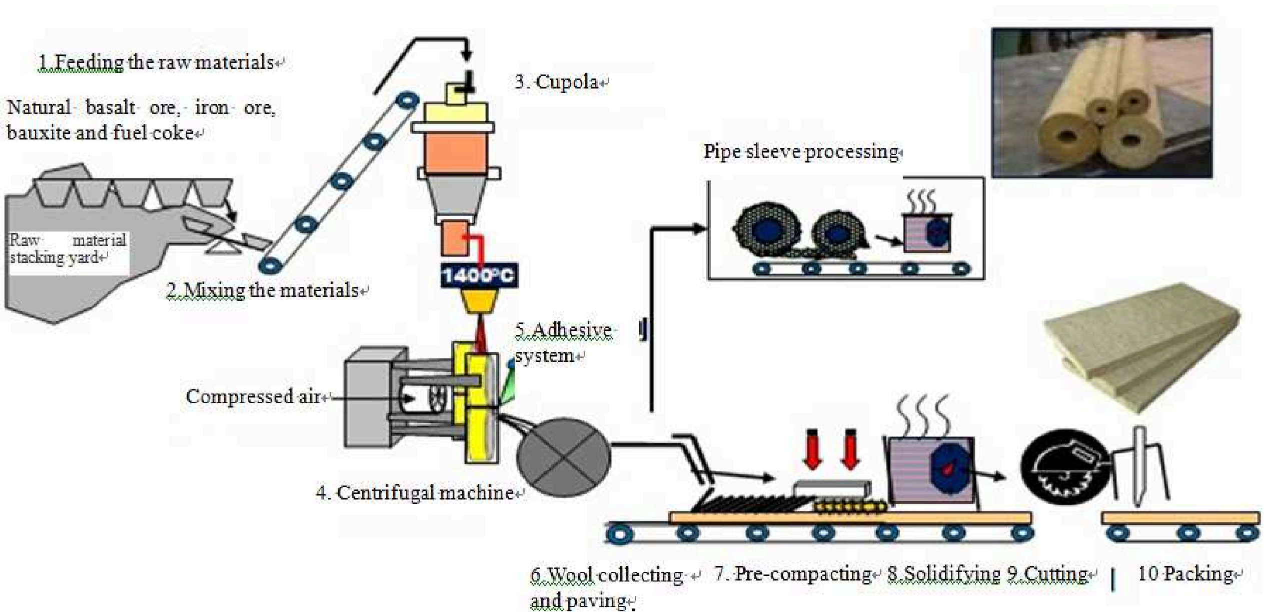

Fig. 2 Production technology flow of rock wool board

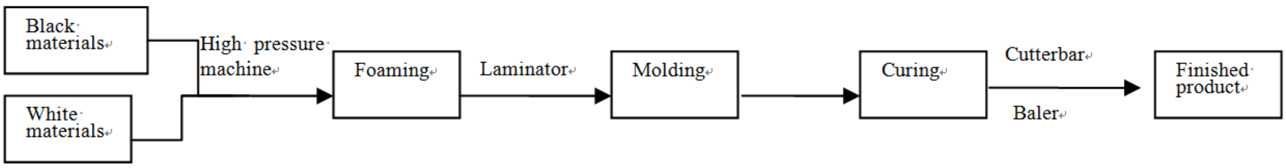

Fig. 3 Production technology flow of rigid foam polyurethane board

Data collection. The list for data collection of various thermal insulation materials determined in the study adopting “the product production in unit mass(kg)” as the functional unit can been seen in Table 1.

Table 1 List for data collection of various thermal insulation materials

Type		Polystyrene board	Rock wool board	Rigid foam polyurethane board
The production process	Raw material consumption	♦ Consumption amount of vinyl benzene; ♦ Consumption amount of pentane as an foaming agent; ♦ Consumption amount of additive (e.g. dispersion agent, flame retardant, initiating agent etc.).	♦ Consumption amount of basalt; ♦ Consumption amount of dolomite; ♦ Consumption amount of slag; ♦ Consumption amount of phenolic resin.	♦ Consumption amount of organic isocyanate; ♦ Consumption amount of polyether; ♦ Consumption amount of cyclopentane as an foaming agent; ♦ Consumption amount of additive (e.g. flame retardant, catalyst etc.).
	Energy consumption	♦ Consumption amount of coal; ♦ Consumption amount of fuel oil; ♦ Consumption amount of electricity.	♦ Consumption amount of diesel oil; ♦ Consumption amount of coke; ♦ Consumption amount of electricity.	♦ Consumption amount of diesel oil; ♦ Consumption amount of electricity.
	Transportation	Transportation distance of various raw materials and energies		
	Greenhouse gas emission	CO_2 emission amount in the production process		
Upstream process		♦ Vinyl benzene production; ♦ Pentane production; ♦ Additive production (e.g. dispersion agent, flame retardant and initiating agent etc.); ♦ Coal production; ♦ Fuel oil production; ♦ Electricity production; ♦ Highway transportation.	♦ Basalt exploitation; ♦ Dolomite exploitation; ♦ Phenolic resin production; ♦ Diesel oil production; ♦ Coke production; ♦ Electricity production; ♦ Highway transportation.	♦ Organic isocyanate production; ♦ Polyether production; ♦ Cyclopentane production; ♦ Additive production(e.g. flame retardant and catalyst etc.); ♦ Diesel oil production; ♦ Electricity production.

The data for raw material consumption, energy consumption and transportation of unit item in the production stage of the three thermal insulation materials are mainly the investigation findings of typical domestic companies. Among them, the dispersion agent, initiating agent, flame retardant and other additives are used in very few amounts in the production of polystyrene board and rigid foam polyurethane board, so such consumption mounts were neglected in the data collection. The data for direct CO_2 emission due to energy combustion in the production stage of each thermal insulation material is obtained by theoretical calculation basing on the *"IPCC Guidelines for National Greenhouse Gas Inventories"*[10].

The data for upstream process involved in the study are obtained from the international and domestic open databas[11-13]. In view of the lack of relevant basic databases in China, the databases for vinyl benzene and foaming agent etc. are used instead. See Table 2.

Table 2 Sources of upstream process data determined in this study.

Production process	Database
Electricity/fuel oil/coal production/highway transportation	♦ Database of Beijing University of Technology; ♦ CLCD database of Sichuan University.
Production of vinyl benzene/foaming agent/phenolic resin/isocyanate/polyether glycol	ELCD2 & Ecoinvent

Evaluation of findings. Inventory analysis on the three thermal insulation materials for the abiotic depletion potential (ADP), primary energy demand (PED) and global warming potential (GWP) in the production life cycle of product in unit mass (kg) is conducted, and the characterization calculation is performed. The results can be seen in Table 3 and Fig. 4.

Table 3 Characterization results comparison of production of three thermal insulation materials in unit mass

Type	Polystyrene board	Rock wool board	Polyurethane board
ADP, kg Coal-R eq./kg board	5.272E+01	1.430E+01	3.540E+01
PED, kg ce eq./kg board	3.951E+00	1.228E+00	3.063E+00
GWP, kg CO_2 eq./kg board	5.636E+00	2.368E+00	5.215E+00

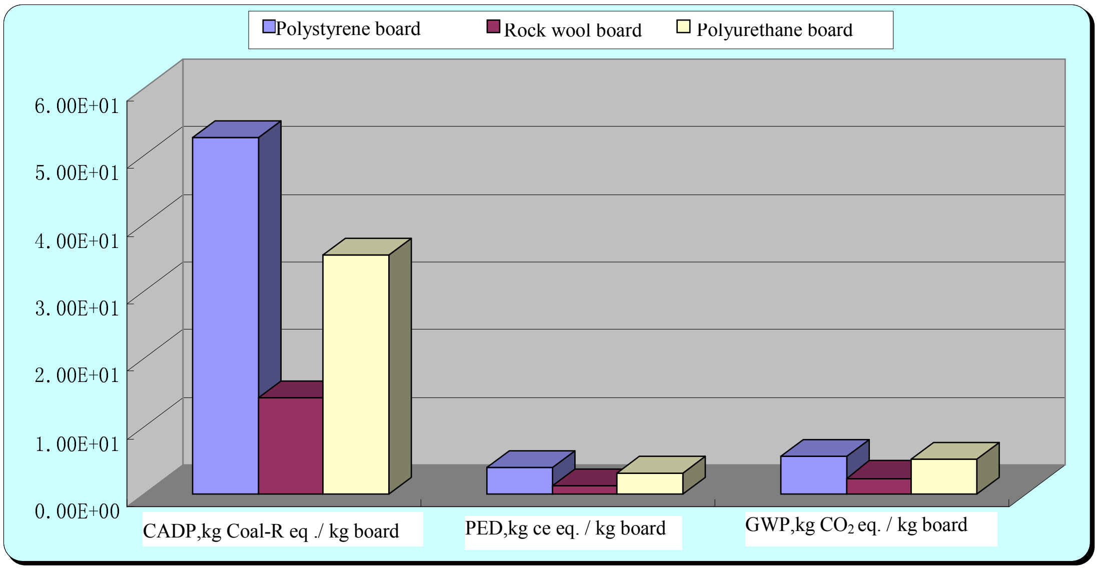

Fig. 4 Characterization result comparison of production of three thermal insulation materials in unit mass

As shown in the results, where calculated in unit mass, the abiotic depletion potential, primary energy depletion potential and global warming potential of rock wool board are all the lowest among those of the three materials. The higher ones are those of the polyurethane board, whereas the environmental impact of polystyrene board production is the highest. Namely, the order of production life cycle environmental impact significances of the three kinds of insulation boards is as follows: rock wool board < polyurethane board < polystyrene board.

Life Cycle Assessment for Production of Insulation Board in Unit Area Meeting the Same Energy-saving Requirements

Energy-saving is the most important attribute of the application of thermal insulation materials to buildings. The difference in environmental friendliness among thermal insulation materials should be compared based on the same energy-saving effect. Therefore, this study, based on the life cycle assessment study of production of insulation board in unit mass, has extended the functional unit to "production of insulation board in unit area (m^2) meeting the same energy-saving requirements", and has been carried out separately in three regions, i. e., the severe cold region, the cold region and the region with hot summer and cold winter, considering the employment characteristics of different thermal insulation materials in different regions.

Determining the thickness of each thermal insulation board meeting the same energy-saving requirements. The thickness of each thermal insulation board meeting the same energy-saving requirements in each region should be determined first so as to obtain the production life cycle environmental impacts of thermal insulation boards in unit area (m^2) meeting the same energy-saving requirements in each region. The preset parameters include:

1) The structural wall body is preset to be "170 mm reinforced concrete wall".

2) According to JGJ 26-2010, "Design Standard for Energy Efficiency of Residential Buildings in Severe Cold and Cold Zones"[14] and JGJ 134-2010, "Design Standard for Energy Efficiency of

Residential Buildings in Hot Summer and Cold Winter Zone"[15], the outer wall heat transfer coefficients ($W/m^2.k$) for severe cold region, cold region and region with hot summer and cold winter are determined respectively as 0.4, 0.5 and 1.

3) Heilongjiang Province, Beijing Municipality and Shanghai Municipality are selected as the representatives of the severe cold region, the cold region and the region with hot summer and cold winter, respectively, and the correction coefficients and heat conductivity coefficients of insulation boards are determined based on the 65% energy-saving design of the current standard.

The thicknesses of three kinds of insulation boards based on the above preset parameters were calculated and the results are shown Table 4.

Table 4 Thickness of each insulation board meeting the same energy-saving requirements

Product	Region	Heat conductivity coefficient, W/(m·K)	Correction coefficient	Thickness , mm
Reinforced concrete	Severe cold (e.g. Heilongjiang Province)	1.74	——	170
	Cold(e.g. Beijing Municipality)	1.74		
	With hot summer and cold winter (e.g. Shanghai Municipality)	1.74		
EPS board	Severe cold (e.g. Heilongjiang Province)	0.042	1.2	120
	Cold (e.g. Beijing Municipality)	0.039	1.05	80
	With hot summer and cold winter (e.g. Shanghai Municipality)	0.042	1.1	40
Rigid foam polyurethane board	Severe cold (e.g. Heilongjiang Province)	0.033	1.05	85
	Cold (e.g. Beijing Municipality)	0.024	1.1	50
	With hot summer and cold winter (e.g. Shanghai Municipality)	0.027	1.1	30
Rock wool board	Severe cold (e.g. Heilongjiang Province)	0.045	1.2	130
	Cold (e.g. Beijing Municipality)	0.04	1.1	85
	With hot summer and cold winter (e.g. Shanghai Municipality)	0.04	1.2	45

Evaluation of findings. Assuming that the volume weights of rock wool board, polyurethane board and polystyrene board are 150kg/m^3, 50kg/m^3 and 20kg/m^3, respectively, calculation of the production life cycle abiotic depletion potential, primary energy depletion potential and global warming potential of each insulation board in unit area (m^2) meeting the same requirements based on the LCA calculation results of the production of insulation board in unit mass (kg) and the insulation board thicknesses meeting the set energy-saving requirements of each region were performed. The results can be seen in Table 5 and Fig. 5.

Table 5 Production life cycle environmental impact of each insulation board in the unit area (m2) meeting the same energy-saving requirements.

Product	Region	ADP, kg Coal-R eq./m^2 board	PED, kg ce eq./m^2 board	GWP, kg CO_2 eq./m^2 board
Rock wool board	Severe cold (e.g. Heilongjiang Province)	2.79E+02	2.39E+01	4.62E+01
	Cold (e.g. Beijing Municipality)	1.82E+02	1.57E+01	3.02E+01
	With hot summer and cold winter (e.g. Shanghai Municipality)	9.65E+01	8.29E+00	1.60E+01
Polyurethane board	Severe cold (e.g. Heilongjiang Province)	1.50E+02	1.30E+01	2.22E+01
	Cold (e.g. Beijing Municipality)	8.85E+01	7.66E+00	1.30E+01
	With hot summer and cold winter (e.g. Shanghai Municipality)	5.31E+01	4.59E+00	7.82E+00
Polystyrene board	Severe cold (e.g. Heilongjiang Province)	1.27E+02	9.48E+00	1.35E+01
	Cold (e.g. Beijing Municipality)	8.44E+01	6.32E+00	9.02E+00
	With hot summer and cold winter (e.g. Shanghai Municipality)	4.22E+01	3.16E+00	4.51E+00

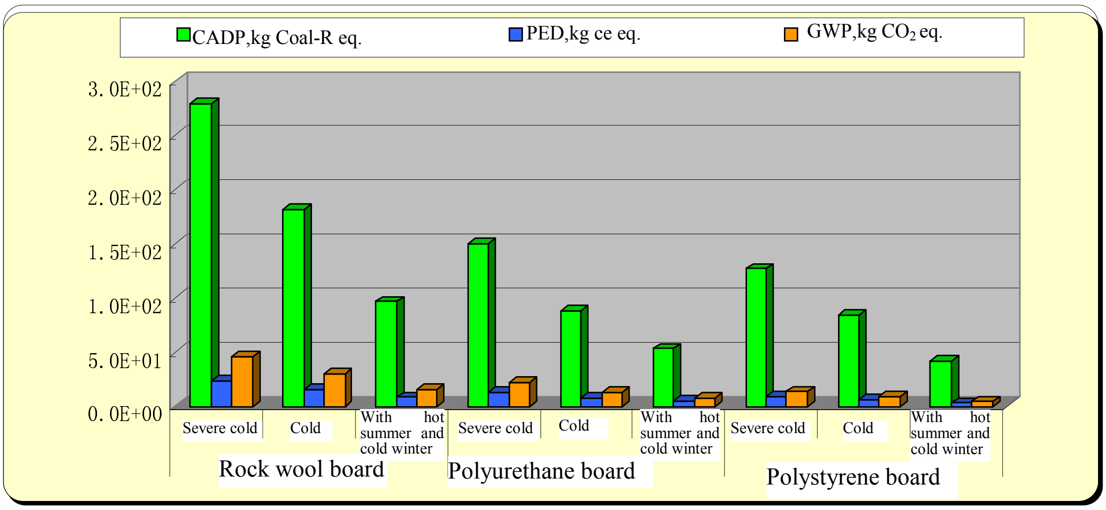

Fig. 5 Production life cycle environmental impact of each insulation board in the unit area (m2) meeting the same energy-saving requirements.

As shown in the results, whatever the region is, in unit area (m^2) meeting the 65% energy-saving requirements, the abiotic depletion potential, primary energy depletion potential and global warming potential of polystyrene board are lower compared with the others, and the second is those of the polyurethane board, which means that the impact of rock wool board is the greatest. Namely, the production life cycle environmental impact significances of the three kinds of insulation boards can be sorted as: polystyrene board < polyurethane board < rock wool board, which is opposite to that of the results for insulation boards in unit mass (kg). The reason for such difference is that they have different volume weights and heat conductivity coefficients. The polystyrene board has a smaller volume weight and the smallest heat conductivity coefficient, whereas the rock wool board has the highest volume weight and heat conductivity coefficient.

Conclusion

(1) Calculated in unit mass, kg, the significances of production life cycle environmental impact of the three kinds of thermal insulation materials can be sorted as: rock wool board < polyurethane board < polystyrene board.

(2) Calculated in unit area, m^2, the significances of production life cycle environmental impact of the three kinds of thermal insulation materials can be sorted as: polystyrene board < polyurethane board < rock wool board

(3) The reason for such a difference is that various thermal insulation materials have different volume weights and heat conductivity coefficients. The polystyrene board has a smaller volume weight and the smallest heat conductivity coefficient, whereas the rock wool board has the highest volume weight and heat conductivity coefficient.

Recommendation

Product life cycle environmental impact is one of the important examination indicators in the selection of green building materials, but it is not all that we should consider about. It shall be included in the organic and united comprehensive evaluation system of green building materials, together with the usability, durability, fire safety and functionality etc..

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