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Performance Research and Application Progress of Thermal Insulation Materials for Cold Storage

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Abstract: The thermal insulation performance of thermal insulation materials for cold storage has a great influence on the energy saving of cold storage, so many scholars have done a lot of research on it. This paper summarizes the production, application, and performance analysis of Polyurethane foam plastics (PU), Expanded polystyrene (EPS), Extruded polystyrene (XPS), and rock wool for cold storage, and summarizes the thermal insulation application of civil-type cold storage, steel structure cold storage, prefabricated cold storage and cold storage pipeline, as well as the cold storage anti-cold bridge measures.

Keywords: Cold storage; Thermal insulation material; Thermal insulation performance; Cold bridge.

1. Introduction

"Dual-carbon" is a major strategic decision made by China to achieve global sustainable development, and to achieve the "dual-carbon" goal, energy saving and consumption reduction are imperative [1]. According to the incomplete statistics of the Cold Chain Logistics Committee of China Federation of Logistics and Purchasing, by the end of 2022, the national cold storage capacity reached 89.38 million tonnes; the new storage capacity in 2022 was 1,080 tonnes, a year-on-year growth of 13.74 %. With the development of cold chain logistics, the development of domestic cold storage construction has great prospects, however, the energy consumption of cold storage has also become the main problem faced by China's cold storage, cold storage enclosure heat transfer accounted for the cold storage of the total heat load of the 25 % ~ 30 %, so the cold storage insulation design is particularly important [2].

The purpose of cold storage enclosure insulation is to reduce the external environment through the enclosure structure into the cold storage heat while avoiding the high-temperature side of the wall condensation phenomenon. In refrigeration installations, the temperature of the equipment and piping in the low-pressure system is also lower than the ambient temperature, so to reduce the loss of cold, it is necessary to insulate the equipment and piping [3][4]. This paper mainly summarises the application process and performance of cold storage insulation materials and reviews the insulation of different types of cold storage enclosures and refrigeration systems.

2. Insulation Material Production and Application Process

Insulation materials are broadly classified into inorganic and organic insulation materials [5]. Inorganic insulation materials include rock wool, glass wool, perlite, aerogel, and vacuum insulation panels (VIP). Most of the inorganic thermal insulation materials have the characteristics of low thermal conductivity, stability, non-toxicity, etc, but due to the lack of load-bearing capacity, they can only be applied to the assembly system of the enclosure structure, in which aerogel, vacuum insulation board (VIP) and other new inorganic materials are too high in cost and cumbersome in the production process, resulting in the fact that they are not widely used. Organic thermal insulation materials have good thermal insulation performance, small weight capacity, small water absorption rate, and other characteristics, such as Polyurethane foam (PU), extruded polystyrene (XPS), expanded polystyrene (EPS), and other thermal insulation materials, are widely used in cold storage enclosure structure.

2.1. Polyurethane foam

Polyurethane foam has become the most widely used thermal insulation material due to its good thermal insulation effect and low price. Polyurethane in the use of the main on-site foaming and made of prefabricated panels in two forms. Polyurethane foam is sprayed directly onto the position of the required thermal insulation under high-temperature conditions, waiting for thirty minutes for it to cool down and set its shape, and finally forming a bubble-like structure. The polyurethane foaming process makes the polyurethane occlusion rate high and can be completely adhered to the voids and junctions so that the thermal insulation layer insulation effect is good, and waterproof properties [6]. Polyurethane can also be prefabricated into polyurethane sandwich panels, which consist of two layers of waterproof color-coated metal sheets panels, which are injected with flame retardant polyurethane rigid foam composite in the middle [7]. Polyurethane sandwich panels have good thermal insulation performance, high strength, and good water resistance, and the length of polyurethane sandwich panels can be determined according to the design requirements and installation conditions or can be cut and processed on-site, making them easy to use [8].

2.2. Extruded polystyrene

Extruded polystyrene panels are rigid foam panels that are extruded by adding a catalyst to a mixture of heated polystyrene and other polymers. Extruded polystyrene has a closed-cell structure with a lower thermal conductivity than polystyrene, which provides better thermal insulation. Due to

the closed-cell structure of its inner layer, it has better moisture resistance and maintains good thermal insulation properties in a humid environment. Because of its high compression strength, it is often used as an insulating material for the floor screeds of cold storage [9]. Extruded panels should be laid with staggered seams and the seams should be sealed with tape to prevent displacement of the insulation panels [10].

2.3. Expanded Polystyrene

Expansion agent styrene (EPS) is formed by polystyrene through the foaming polymerization of a closed cavity structure of light polymer [11]. EPS because of the closed cavity of this unique structure has the advantages of low cost, lightweight, high strength, durability, and so on, in high-temperature cold storage has been widely used. In the cold storage construction, the EPS module is assembled into a cavity by block-type staggered seams, placed in the internal reinforcement, concrete, internal and external surfaces with granular slurry smearing, smearing adhesive paste plus glass fiber mesh, constituting a cold storage enclosure structure with heat preservation and load-bearing integration. Adopting EPS can make the cold storage with good thermal insulation performance and seismic performance, and low construction cost.

2.4. Rock wool

Rock wool is a kind of inorganic thermal insulation material made of basalt, basalt, iron slag, and other main raw materials, binder, fire retardant, and preservatives as additives, after high-temperature melting, through the fibrillation process. Rock wool composite board is the main application form of cold storage insulation, it is made of two layers of metal plate and rock wool composite, rock wool composite board through the light steel keel and masonry connection, rock wool composite board between the joints of polyurethane foam filling, the use of airtight adhesive and non-woven fabric sealing. Rock wool composite panels are lightweight, tightly structured, easy to install, and can effectively improve the construction efficiency of cold storage [12].

3. Performance Analysis of Insulation Materials for Cold Storage

3.1. Polyurethane foam

Polyurethane foam (PU) is widely used in the field of cold storage because of its non-toxicity, low density, low thermal conductivity, sound absorption, and long life [13]. However, polyurethane foam has the disadvantages of flammability and low strength, which can easily cause fire accidents in use and is prone to deformation, resulting in reduced thermal insulation performance.

To enhance the flame retardancy of PU, domestic and foreign scholars have carried out a lot of research, Beata Z et al [14] added 5 %-20 % of microsphere materials with spherical glassy aluminosilicate particles in the preparation of polyurethane insulation materials, and the results showed that the addition of microsphere materials in polyurethane foams was able to reduce the flammability of PU, and the coefficient of thermal conductivity was 0.032 W/(m -k). In addition, the addition of flame retardant is also a very effective solution, Gong Qirui et al [15] added a flame retardant combining hyperbranched polyol containing three flame retardant elements of P, N, and Si with expanded graphite in polyurethane foam, and the results showed that the limiting oxygen index in vertical combustion test is V-0, and this polyurethane foam has excellent flame retardant properties and smoke suppression effect.

Improving the compressive strength of polyurethane foam is also a research focus of polyurethane foam. Jie et al[16] added 5 % of P/Cu hybridized silica aerogel to polyurethane foam. The results showed that the compressive strength of the composite foam material was increased by 52.2 %, which provided an effective method for designing high-performance materials. Yingming Li et al [17] designed a scheme based on PVA-ATP aerogel to prepare polyurethane foam composites with a unique three-dimensional reticulated structure, and the compressive strength of the composites reached 338 KPa by testing.

3.2. Extruded polystyrene

Extruded polystyrene is characterized by closed cell structure, low water absorption, low thermal conductivity, corrosion resistance, and good durability. However, the limiting oxygen index is only 17 %, which produces a large amount of black smoke and toxic gases during combustion, so it is very important to develop flame retardant extruded polystyrene. Guo Xiaorong et al [18] used modified glucose (MCG) as the carbon source and ammonium polyphosphate (APP) as the acid source, and coated XPS boards with flame retardant by compounding, and the results showed that the ultimate oxygen index of XPS insulation boards could reach 32.4 % and the vertical combustion grade could reach V-0 when the mass ratio of APP: MCG was 3:1, with a significant flame retardant effect. González A et al [19] combined the gypsum and extruded polystyrene waste to make a new lightweight building material, and the results showed that the addition of gypsum improved the thermal resistance of XPS, and the thermal conductivity was reduced by 37.6 % compared with XPS without gypsum.

3.3. Expanded Polystyrene foam

Expanded polystyrene foam has the advantages of low cost, lightweight, high strength, and good durability due to its closed cavity structure, and is widely used in high-temperature cold storage. However, the water absorption rate of expanded polystyrene foam is high, and the water absorption rate has a significant effect on the thermal conductivity, with the increase of water absorption, its thermal conductivity also increases, and the heat preservation effect becomes worse [11], and this material is flammable, and harmful gases will be released when it burns.

Researchers and scholars have done many studies to develop expanded polystyrene foam with water repellency and flame retardancy. Shi et al [20] prepared a new composite thermal insulation material (NTIC) by combining industrial solid waste with EPS and the results showed that the samples with a compression ratio of 1.8 had better performance with a water absorption of 8.04 % and a thermal conductivity of 0.048 W/(m•k), and all the samples did not burn under the flame. Parastoo F M et al [21] combined a recycled plastic layer and EPS insulation board to make a composite insulation material, and the results showed that the three-layer composite material reduced water absorption by 18 % and delayed flame spread.

3.4. Rock wool

Rock wool has good thermal insulation, durability, fire resistance, and acoustic absorption due to its porous fiber structure, but it is easy to absorb the moisture in the environment, which leads to the material's thermal conductivity becoming larger and reducing the thermal insulation effect. Researchers and scholars at home and abroad have done a lot of research to enhance the water resistance of rock wool, Yan Qiuhui et al [22] used the seepage immersion and ambient pressure drying method to prepare silica aerogel/rock wool composite panels. The results show that when the mass fraction of silica aerogel is 8 % and the infiltration time is 20 min, the thermal conductivity of the composite insulation board is 0.0333 W/(m-k), which is 26.7 % lower than that before the modification, its water absorption is 0.78 kg/m3, which is 35 % lower, and the compressive strength is 7 % higher. Hao Wentao et al [23] used PDMS/SiO nanoparticles as a modifier to modify rock wool by dip-coating method, and the experimental results showed that the modified rock wool could completely float on the water surface, and the water contact angle was 152.9 °, and the modified rock wool had superhydrophobicity.

Table 1. Performance parameters of thermal insulation materials

Heat insulator	Thermal conductivity/ ($W•m^{-1}•k^{-1}$)	Scale of burning	Density / ($kg•m^{-3}$)
Polyurethane	0.016-0.024	B2/B1	30-40
XPS	0.025-0.035	B2	32-40
EPS	0.031-0.037	B2	15-35
Rock wool	0.033-0.046	B1	40-200

4. Insulation of Cold Storage Buildings

According to the structural classification of cold storage, cold storage is broadly divided into three types: civil cold storage, steel structure cold storage, and assembly cold storage. The choice of cold storage type is affected by geographical location, investment cost, and other factors.

4.1. Insulation of earth-built cold stores

Civil cold storage is a kind of cold storage with more construction, and the main body of the building is generally a reinforced concrete frame structure or brick concrete structure. Civil cold storage capacity, low cost, long service life, the use of proper maintenance of the case can be used for decades.

To increase thermal insulation performance and reduce the cost of large-scale civil cold storage, polyurethane on-site spraying is mostly used [24]. Fan Guojun et al [25] in the enclosure insulation within the wall insulation and roof insulation using B1 grade polyurethane spraying, cold storage insulation effect is good, and the unit power consumption is small. Gansu Province, Lintao County, fruit and vegetable preservation library subsidy project cold storage, direct spraying 80 mm thick, B1 level polyurethane, this enclosure structure can reduce the loss of cold storage, reduce costs, while the development of the local vegetable industry can be improved [26].

A metal sandwich panel is more stable in terms of heat preservation effect compared to polyurethane spraying, and the enclosure material of new concrete cold storage generally adopts a polyurethane sandwich color steel plate or XPS heat preservation board. Cai Yuanyuan et al [27] used single-sided color steel plate composite heat preservation technology in civil cold storage, the technology is directly the wall, polyurethane heat preservation material, and single-sided color steel plate one-time combination molding, forming no joints, color steel plate veneer overall heat preservation, which not only solves the problem of unevenness and deformation of the surface of the color steel plate board but also improves the quality of the wall heat preservation and the ability of anti-collision. Taikoo Cold Chain Logistics Ningbo project in the use of ultra-flat floor construction process, laying four layers of 100 mm extruded polystyrene insulation board in layers of staggered seams, with high-strength polyurethane foam filling the gap, the height according to the thickness of the insulation layer [28], the project has been put into use for three years, the floor did not bulge phenomenon, the library temperature stability is good, energy-saving efficiency is obvious.

4.2. Insulation of steel structure cold storage

Steel structure cold storage consists of a steel structure frame and cold storage partition wall, heat preservation often use prefabricated library board on-site splicing form, and has the advantages of high strength, lightweight, and ease to install, the disadvantage the poor integrity, investment costs and maintenance costs are higher.

Traditional large-scale steel structure cold storage has problems such as poor integrity and large demand space [29]. Jiang Quansheng [30] in the project of steel structure cold storage in the Xiamen airport logistics park, the thermal insulation library board adopts a double-sided color steel polyurethane sandwich panel, the ground is laid with rigid extruded plastic thermal insulation board, and the joints are filled with foamed polyurethane, and this structure makes the cold storage heat preservation effect is good, and it can shorten the period and save the cost. Wang Bin [31] used a new type of wall material (shown in Fig. 1) that incorporates vapor compression and aerated technology, the thermal insulation wall material is divided into four different types according to different bulk densities, as shown in Table 2, which can be selected according to the thermal insulation needs of the steel structure cold storage from several aspects such as strength level, and this new type of wall material improves the airtightness and thermal insulation of the cold storage.

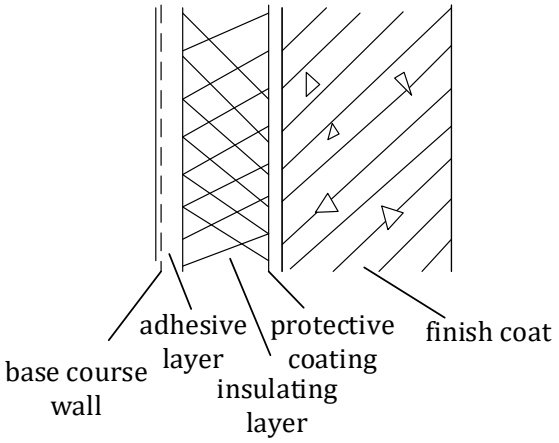

Figure 1. Basic structural drawing of new autoclaved aerated technology wall materials

Table 2. Technical indexes of four different types of energy-saving thermal insulation wall materials

Level	Strength level	volume density / (kg/m^3)	Drying shrinkage / (mm/m)	Post-freezing strength / (Mpa)	Thermal conductivity/ (W/m·k)
B003	A1.0	320	0.1	0.7	0.12
B004	A1.5	390	0.25	1.2	0.16
B005	A2.5	450	0.35	2.6	0.16
B006	A7.5	650	0.50	2.8	0.18

In other building renovations cold storage projects generally use the form of internal heat preservation, and heat preservation materials are generally polyurethane sandwich panels. Hubei Province, a vaccine cold storage transformation project using the original workshop steel structure, walls, and roof panels used to lay 100 mm thick, B1 level polyurethane sandwich panels, the ground laying two layers of 50 mm thick, B1 level XPS board [32], tested, the temperature inside the library is uniform and stable, to meet the design requirements. In a steel structure production plant renovation cold storage project, the envelope insulation material used polyurethane sandwich insulation board, and ground insulation used high-density XPS board [33], after testing, the temperature inside the library to meet the design requirements, the insulation effect is good.

Roof and ground insulation is also very critical. Improper insulation of the roof and ground directly affects the insulation effect of the whole cold storage. In the Guangdong cold chain series project, the pre-buried heating pipe ground construction method is used, combined with the XPS board layered laying paste cold process (shown in Figure 2), this method can not only reduce energy consumption but also achieve the purpose of reducing the ground freezing [34]. Guangzhou Changyun warehousing logistics cold storage project, the use of external insulation roof waterproofing system, the thermal insulation layer using three layers of 100 mm + 100 mm + 50 mm thick XPS insulation board, plus a layer of PE vapor barrier and 40 mm thick rock wool insulation board [35], insulation boards staggered seams connection, the seams using polyurethane foam spray, the use of this system solves the traditional roofing airtightness is poor, heat preservation discontinuity and leakage problems. and leakage problems.

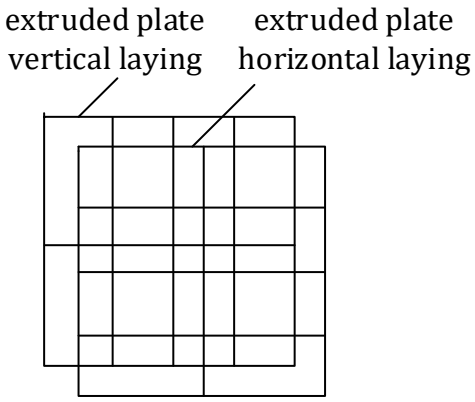

Figure 2. XPS extruded board layered paving plane

4.3. Insulation of assembled cold rooms

Assembly cold storage is a kind of on-site assembly cold storage, mainly using a lightweight composite sandwich panel as the enclosure structure. Due to the advantages of large space inside the warehouse, short construction period, quick installation, and beauty and hygienic, it is more and more favored by users.

The assembled cold storage mostly uses polyurethane sandwich panels as thermal insulation materials. Fan Guojun et al [25] used a double-layer compressed steel plate composite insulation roof for the roof envelope and double-sided color steel polyurethane sandwich panels for the wall body and ceiling insulation in the assembled cold storage of the Guangdong cold chain backbone network. This structure makes the cold storage heat preservation effect good, the internal space becomes bigger, improving the space utilization rate. Lintao County, Gansu Province, one hundred tonnes of fruits and vegetables assembled freshness storage (shown in Figure 3) uses 150 mm thick, B2 level polyurethane double-sided color steel plate, which not only reduces the loss of cold storage but also increases the internal space of the cold storage [26].

Figure 3. Ruit and vegetable fresh-keeping warehouse

The assembly cold storage can also use XPS insulation board as thermal insulation material. Liu Fu Yafu et al [36] in the multi-story assembled cold storage project using external insulation process, insulation board using three layers of XPS insulation board (thickness of 100 mm, 100 mm, 50 mm), plus a layer of polyethylene vapor barrier and 40 mm thick rock wool board fireproofing layer (shown in Figure 4), the ground thermal insulation using a double XPS extruded polystyrene panels, the joints of the spray polyurethane foam to cut off the cold bridge and strengthen The results show that this insulation system not only improves the construction efficiency but also saves insulation materials [37]. Jiang Xiangyang et al [38] in the Guangzhou Changyun warehouse cold storage project adopts an external insulation process, the roof is laid with XPS insulation boards with staggered seams, and the ground insulation layer adopts 200 mm thick XPS (500 kPa) extruded plastic boards (shown in Fig. 5), and the simulation calculation shows that, compared with the conventional cold storage, the energy saving rate of the project is 9.99 %, which is a significant energy-saving effect.

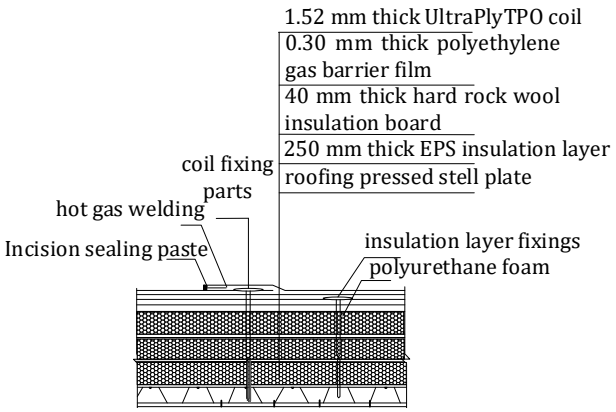

Figure 4. Joint details of roof waterproof and thermal insulation system

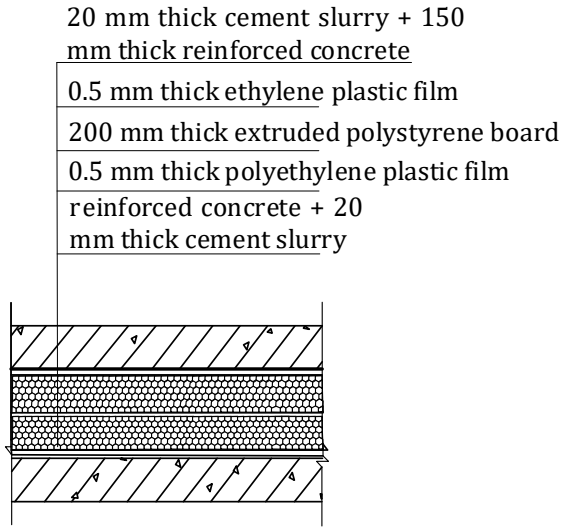

Figure 5. Details of the joint of floor and ground gas insulation system

In addition, you can also use metal rock wool sandwich panels as thermal insulation materials, Liu Zhiyong et al [12] in Wuxi Wanda Mao Entertainment Snow Park cold storage project, wall and roof insulation using 240 mm thick metal rock wool sandwich panels, the interface with polyurethane foam filling (shown in Figure 6), this structure does not require secondary processing, cost savings, and improve the construction efficiency.

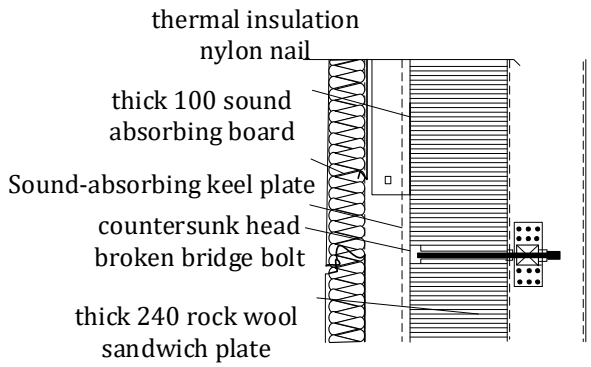

Figure 6. Wall insulation structure

4.4. Insulation of cold storage refrigeration system pipes

To reduce the loss of cold and prevent dew on the surface of the pipeline, the refrigeration pipeline working at low temperatures and low pressure should be insulated. At present, the main insulation material used is polyurethane foam.

Pipes that need to be kept cold include medium- and low-pressure gas pipes and liquid pipes, high-pressure subcooled liquid pipes and exhaust pipes, hot ammonia frost flushing pipes, and upper and lower water pipes that go through low temperatures. Xiang Xiaoying et al [39] in the Guangzhou Changyun warehouse project in the cold storage pipe insulation in the whole once the foam insulation technology, the technology according to the thickness of the insulation, in the pipeline outside the stainless steel plate fixed a concentric circle, with polyurethane in the internal foam, so that the pipeline, the insulation layer, the shell to form a whole. This technology effectively ensures the quality of the pipeline connection, and reduces impurities in the pipeline, there are good economic and social benefits. A large cold storage ammonia refrigeration pipe insulation is made by 120 mm thick polyurethane casting, and 0.5 mm thick 304 stainless steel is used as the protective shell, which not only meets the demand for insulation but also extends the service life [40].

5. Cold Bridge Identification and Bridge-Breaking Techniques in Cold Storage Buildings

Cold storage thermal insulation structure in the local structure of the different, caused by the part of the thermal insulation performance is reduced, become a large number of the cold transmission channel, known as "cold bridge". Cold bridge is caused by the cold storage project insulation layer bad and loss of thermal insulation effect of important reasons, many cold storage due to the cold bridge is not dealt with, resulting in serious economic losses [41] [42].

To reduce the cold bridge, the following aspects can be considered: firstly, make the heat insulation layer vapor barrier and moisture barrier of each part of the enclosure structure connect as a whole, avoiding direct contact between the heat insulation layer and the outside air. Jian Zhang [43] used polyurethane foam filling at the junction of wall panels and roof panels, insulation panels and wall surfaces, and polyurethane sealant sealing between the slot panels and the isolation layer in the steel structure cold storage. The results show that the generation of cold bridge can be effectively controlled and the loss of cold energy can be reduced. At the cold bridge of the steel structure column of the supporting cold storage of a supermarket in Henan, a polyurethane heat preservation pad with a compressive strength of 30 Mpa was used, which not only meets the requirements of heat insulation but also plays a role in supporting the load[29]. Secondly, heat insulation, vapor insulation, and moisture-proof treatment are carried out around the part of forming a cold bridge to avoid frost and ice on the high-temperature side[43]. Jiang Xiangyang et al [38] in the assembly cold storage, to reduce the cold bridge to take measures in the wall purlin, steel purlin, steel beams, diagonal tie rod surface spraying polyurethane insulation material, the trough part of the steel plate is filled with polyurethane foam, this method can effectively control the generation of the cold bridge, reduce the loss of cold energy.

Due to the cold storage structure and other factors cold bridges can not be completely avoided, the design of cold storage needs to take certain measures to reduce the impact of cold bridges to reduce economic losses.

6. Conclusions

Cold storage commonly used insulation materials including polyurethane foam (PU), expanded polystyrene (EPS), extruded polystyrene (XPS), rock wool, etc., their production and application process and performance differences, for the shortcomings of each type of material, scholars have carried out a lot of application of the improvement of the study and achieved significant results. In different types of cold storage enclosures and pipe insulation, PU and XPS are more widely used. However, the waterproof and thermal insulation can still be improved, EPS due to the thickness of large, poor fire and waterproof performance, and other shortcomings, so the application of the cold storage has been limited. Rock wool due to easy moisture absorption, easy aging, and other shortcomings also limits the application of cold storage. In addition, new inorganic thermal insulation materials such as vacuum insulation panels (VIP), aerogel, etc. have a broad research prospect in cold storage, however, these materials have low mechanical properties, high cost, and other problems, and there are some limitations in the future development. Therefore, it is necessary to further explore the research in the future to obtain lower-cost, high-performance insulation materials for cold storage.

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