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Review Article

Freeze-Thaw Resistance of Thermal Insulating Materials Used in Cold Regions Engineering: A State-of-the-Art Review

Lingjie Li,[1,2] Dongna Li ,[3] Xiaoming Zhu,[4] Kun Zhang,[5] and Yanhu Mu [1,2]

[1]*State Key Laboratory of Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China*
[2]*University of Chinese Academy of Sciences, Beijing 100049, China*
[3]*School of Mechanical Engineering, Lanzhou Jiaotong University, Lanzhou 730070, China*
[4]*Gansu Province Highway Traffic Construction Group Co. Ltd., Lanzhou 730030, China*
[5]*School of Civil Engineering, Northwest Minzu University, Lanzhou 730024, China*

Correspondence should be addressed to Dongna Li; lidongna@mail.lzjtu.cn

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Thermal insulating materials (TIMs) are widely used in roadways, tunnels, airfields, pipeline systems, and buildings in cold regions to prevent infrastructure from freeze damages and reduce energy consumption. During the period of use in cold regions, however, seasonal freeze-thaw actions can cause degradation of thermal and mechanical properties of TIMs and even malfunctions. Lots of research has been carried out on the durability of TIMs under cyclic freeze-thaw (CFT), but comprehensive reviews are scarce at present. Based on a literature review, the state and development of the test apparatus, temperature controls for the CFT test, and changes in the thermal and mechanical characteristics of TIMs during the CFT operations were summarized in this study. The review shows that the CFT can damage the TIMs' microstructure, which will result in an increase in the materials' thermal conductivity and water absorption rate with a decrease in their mechanical strength. However, since the application scenarios of TIMs are various, there are significant differences in previous researches, especially the test conditions. These differences limited the applicability of the test results and make a barrier among researchers and engineers. Thus, a unified test method for the durability of TIMs under the CFTs should be established in the future.

1. Introduction

Infrastructures in cold regions are heavily bothered by damages related to seasonal freeze-thaw actions. In order to mitigate these damages, thermal-insulating materials (TIMs) have been extensively used to insulate infrastructures or foundation soils from severe freeze-thaw actions (Figure 1). In transportation infrastructure, TIMs are generally laid within roadway embankments, airfield runways, and tunnel linings [1–4]. Because of their low thermal conductivity, the heat exchange between the subgrade and the ambient environment could be retarded, and then, damages related to seasonal frost heave and thaw settlement of the subgrades could be mitigated. For residential, commercial, and industrial buildings, insulation with kinds of TIMs is a highly energy-efficient technique that can reduce the dependence on heating, ventilation, and air condition systems to provide a comfortable indoor thermal environment [5, 6]. Thus, TIMs also provide a very important contribution for energy conservation in building sectors. In recent decades, the use of TIMs in building sectors is rapidly growing as energy conservation has become a strategic goal in the context of global warming. For pipeline systems, including district heating pipelines and long-distance energy pipelines in cold regions, TIMs can not only reduce the heat loss of the pipeline systems but also mitigate the freeze-thaw damages [7, 8]. Overall, from the perspective of reducing energy consumption and prolonging the service life of engineering infrastructures, large-scale application of TIMs is of great importance for the sustainable development of cold regions in the world.

Figure 1: TIMs used in (a) roadway embankment, (b) cutting slopes, (c) tunnels, (d) oil pipelines, (e) buildings, and (f) municipal pipelines in cold regions.

TIMs are materials or composite systems that retard the rate of heat flow by conduction, convection, and radiation. They are generally comprised of a solid matrix material with a gaseous material interspersed randomly or regularly within the cells, pores, or interstices [9]. At present, there are numerous types of commercial TIMs used in cold regions engineering. Classification, properties, benefits, and drawbacks of available TIMs used in the building sectors were overviewed and discussed in lots of researches [5, 6, 10]. The TIMs can be divided into inorganic materials (e.g., foam glass, glass wool, rock wool, and expanded perlite(EP)), organic materials (e.g., expanded polystyrene (EPS), extruded polystyrene (XPS), phenol-foam (PF), polyurethane (PU), and polyisocyanurate (PI)), metallic or metalized reflective membranes, and the thermal insulators made from waste materials and composite materials (polymer and concrete composites). About the form, TIMs are generally created in porous, blanket or batt form, rigid, natural foam, and a reflective structure. In addition to these traditional TIMs, a series of modern TIMs with high-performance thermal insulation have been developed in recent decades, including closed cell foam, vacuum insulation panel (VIP), gas filled panel, aerogel, and phase change materials [5, 11, 12]. At present, inorganic fibrous materials including glass wool and stone wool account for 60% of the market and organic foamy materials including expanded and extruded polystyrene and polyurethane account for about 27% of the European market for insulating materials [13].

Due to their low thermal conductivity and low cost, traditional TIMs including PU, PI, XPS, and EPS are widely used in buildings, transportation infrastructures, and pipeline systems in cold regions. During the period of use, TIMs are generally subjected to the effects of weathering and stresses, so they need very high durability [14–16]. In cold regions, the weathering processes on the TIMs are typically stronger and always coupled with other effects together, including radiation, cyclic freeze-thaw (CFT), cyclic dry-wet, and salt erosion. The CFT is a part of the natural weathering process occurring daily or seasonally in cold regions; it is one of the major causes that significantly degrade engineering properties of building and construction materials, e.g., concrete, asphalt, and soils [17–19], as well as TIMs. Thus, the resistance of building and construction materials under the CFTs is of great importance for long-term stability and service performance of engineering infrastructure in cold regions. The CFTs can cause cracks in more porous medium, particularly when moisture participates in this process. When the temperature falls below the freeze point, the water turns to ice and expands by 9% in volume [20–25] and the frost-heaving force will cause the destruction of solid skeleton and cellar [26]. After being subjected to the CFTs, the TIMs would suffer severe microstructure modifications and consequent deterioration in mechanical strength, thermal insulation characteristics, waterproof ability, fire resistance, and so on.

Considering these detrimental effects, studies on freeze-thaw resistance of different TIMs have been widely carried out, which provided important basis for engineering applications and material improvement. However, compared with other construction materials, such as concretes and soils [27–31], studies on freeze-thaw resistance of TIMs are not systematical and normative up to present. The object of this paper is to conduct a comprehensive review and discussion on the freeze-thaw resistance of TIMs used in cold regions. The literatures were gained mainly from journal databases including Elsevier ScienceDirect, SpringerLink, Wiley Online Library, and CNKI. Firstly, experimental methods for CFT on TIMs were introduced based on related requirements and available literatures. The focus was placed on the test apparatus and temperature controls of the CFT. Secondly, changes in thermal and mechanical properties of TIMs under the CFT were summarized. It is hoped that the review can provide reference for future engineering applications and improvement of TIMs used in cold regions.

2. Testing Methods

Studies on the effects of the CFT on the TIMs are generally carried out in the laboratory. TIMs with a specific size or shape are typically put in a temperature-controlled chamber to subject freezing and in a water tank to subject thawing, referred as the CFT test hereinafter. Then, they were transferred to mechanical, thermal, and microstructural tests to determine their freeze-thaw resistance.

Table 1 lists some standards or specifications from home and abroad that are related to the CFT tests of TIMs. In the table, parameters including specimens' size, the number of specimens, freezing/thawing temperature duration time, procedure, and the number of CFTs are given. For thermal-insulation products, such as the TIMs used for unprotected ground insulation, which are regularly exposed to water and low temperatures, the first two criteria are advised. In the two standards, the freezing process of TIMs occurs in a cold chamber with a constant temperature of $-20 \pm 2^\circ C$ and the thawing process of TIMs occurs in a water tank with a constant water temperature of $20 \pm 2^\circ C$. The temperature controls and durations of freezing and thawing processes are illustrated in (Figure 2(a)). To determine their freeze-thaw resistance, the specimens need to experience 300 CFTs.

While the middle three specifications are for external thermal insulation composite systems based on XPS or EPS, the system generally includes wall, adhesive layer, TIM (XPS or EPS), and rendering layer, which are extensively used for external thermal insulation of civil buildings in recent years. As a thermal insulation system is generally fitted on external walls of buildings, the freeze-thaw resistance is quantified in terms of damages, including hollows, desquamate, and fissure, and in tensile adhesive strength between the TIMs and the rendering layer after the CFT test. In one freeze-thaw cycle, specimens are thawing in water at room temperature for 8 hours and then freezing in cold chamber at $-20^\circ C$ for 16 hours, as shown in Figure 2(b). Thus, the duration of each freeze-thaw cycle is 24 hours. After every 3 CFTs, specimens should be taken out to check damages. After 30 CFTs, the specimen will be transferred to the tensile adhesive strength test after a curing process.

The last two specifications are used for determining the freeze-thaw resistance of thermal insulation concrete. The GB/50082 is the standard for long-term thermal performance and durability test of normal concrete [32], while ASTM-666 is the standard test method for resistance of concrete to rapid freezing and thawing [33]. In tests of freeze-thaw resistance of concrete, the freezing and thawing duration are generally determined by temperature variations in the cold chamber or in the specimens. In ASTM-666, it is required to lower the temperature of specimens from $4^\circ C$ to $-18^\circ C$ and to raise the temperature from $-18^\circ C$ to $4^\circ C$ in not less than 2 hours and nor more than 5 hours.

The specifications above provide detailed methods and procedures for the CFT test on TIMs and related thermal insulation systems. In previous laboratory test studies, however, the CFT tests were conducted with kinds of different methods and procedures due to different application scenarios, test apparatus, and even research grant. About the test apparatus, some studies conducted both the freezing and thawing in one automatically temperature-controlled chamber with specimens immersed in water, while some studies conducted the freezing process in a cold chamber and the thawing process in another chamber with a constant temperature and humidity. About temperature controls, $-20^\circ C$ and $20^\circ C$ were widely used for freezing and thawing in previous studies. But there are also lots of studies determined the temperatures based on multiple work environments of TIMs. About freezing/thawing duration time, the differences within previous researches are more significant. In some laboratory tests, the freezing duration was determined by the temperature decrease process of the cold chamber. For example, the temperature control system of the chamber was set as $-20^\circ C$, when the temperature inside the chamber reached $-20^\circ C$, the temperature control was set and kept

Table 1: Test methods and requirements for the CFT test on TIMs in related specifications.

Specifications/standards	Specimen size (cm) ($L \times W \times H$)	NS	FT, TT (°C)	FD, TD (hour)	CFT procedure	NFT
ISO 20394-2007 [34]	$(500 \pm 1) \times (500 \pm 1) \times H$ or $(200 \pm 1) \times (200 \pm 1) \times H$	Determined by following test	-20 ± 2, -20 ± 2	1, 1	(1) Freezing in cold chamber; (2) immerse in water tank	300
GB/T 33011—2016 (ISO 16546: 2012, IDT) [35]	$(500 \pm 1) \times (500 \pm 1) \times H$ or $(200 \pm 1) \times (200 \pm 1) \times H$	Determined by following tests	-20 ± 2, 20 ± 2	1, 1	(1) Freezing in cold chamber; (2) immerse in water tank	300
GB/T 29906—2013 [36]	$600 \times 400 \times H$ or $500 \times 500 \times H$	3	-20 ± 2, room temperature	16, 8	(1) Soak in water tank with water proof; (2) freezing in cold chamber	30
GB/T 30595—2014 [37]	$600 \times 400 \times H$ or $500 \times 500 \times H$	3	-20 ± 2, room temperature	16, 8	(1) Soak in water tank with waterproof; (2) freezing in cold chamber	30
JGJ 144-2019 [38]	$500 \times 500 \times H$	3	-20 ± 2, room temperature	16, 8	(1) Soak in water tank with waterproof; (2) freezing in cold chamber	30
GB/T 50082—2009 [32]	$100 \times 100 \times 100$	3~5	−20~−18, 18~20	2~4	(1) Freezing in cold chamber; (2) soak in water tank	25
ASTM C666/C666M [33]	—	—	-20 ± 2, 4 ± 2	2~5, 2~5	Rapid freezing and thawing in water or rapid freezing in air and thawing in water	36

NS: number of specimens; FT: freezing temperature; FD: freezing duration; TT: thawing temperature; TD: thawing duration; NFT: number of freeze-thaw cycles.

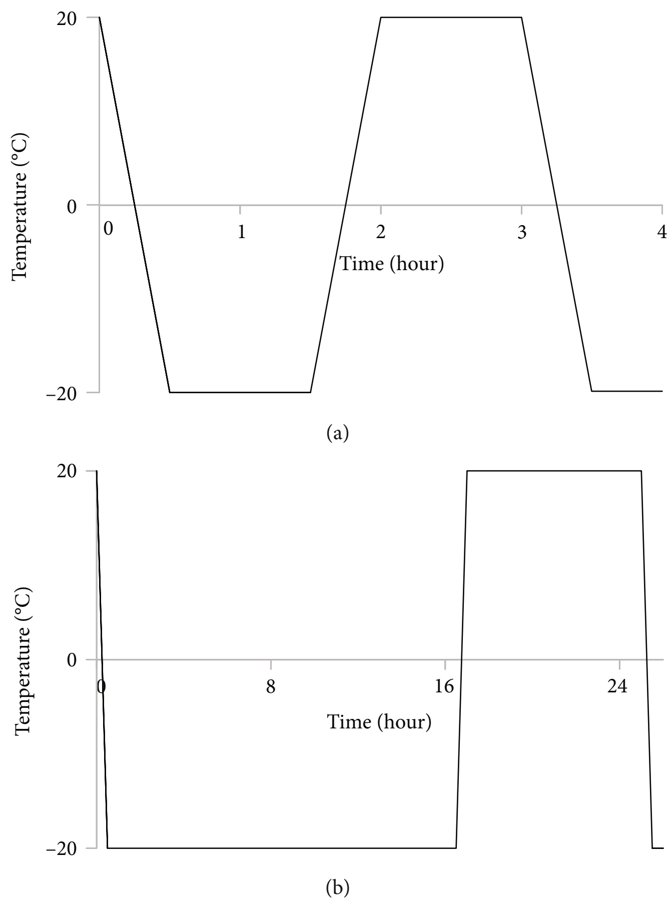

Figure 2: Standard-specified temperature controls in CFT test on (a) thermal-insulation products and (b) external thermal insulation composite system.

constantly as 20°C, and the whole time taken by one freeze-thaw cycle was 6 hours in the study [39]. Furthermore, the freezing and thawing durations also were set as 4 hours and 2 hours, respectively, in some studies [25]. The number of CFTs also differed considerably in previous tests. Some of them conducted the freeze-thaw less than 30 cycles while some conducted the cycles even close to one thousand. In addition, to simulate the working environments of TIMs in actual engineering applications, some studies conducted the CFT test of TIMs considering factors such as stress and saline water [26]. The considerable differences in methods of CFT tests of TIMs make differences in comparison of the test results. These differences also affect the choice of materials in engineering applications and improvement in materials' freeze-thaw resistance.

3. Changes in Physical Properties of TIMs under CFTs

3.1. Water Absorption. Water absorption is an important property of TIMs. It is generally determined as water absorption by diffusion as specified in ISO 20393 [40] or by immersion as specified in ISO 2896 [41]. The former one is to simulate the absorption of water byproduct when it is subjected to water vapor pressure difference and temperature gradient between its upper and lower surfaces for a period of 28 days, while the latter is to measure the buoyant force on a test specimen after immersion under a 50 mm head of water for 4 days. For different materials, the immersion time is always different. For example, in GB/T 5486, the immersion period of 2 hours is typically used for rigid inorganic thermal insulation products [42], while, in ASTM C1763, a two-hour immersion period is also recommended for the cellulosic fiber insulating board and polyisocyanurate thermal insulating board [43].

Due to stress and expansion during the phase transition from water to ice, the freeze-thaw process can damage TIMs' closed pore structure and result in flaws inside. With the increase of the number of CFTs, early-term defects would accelerate this deteriorate process and finally lead to a considerable increase in the water absorption of TIMs. The increase, however, differs considerably for different TIMs and generally related to their skeleton particles and pore structures. The different test methods also contribute to differences in results. Wang et al. tested the change of water absorption of XPS after 200 CFTs and found that the water absorption increased by 9 times and reached 12.5% [39]. Tang et al. [26] conducted a series of CFT tests on PU which was widely used in cold regions tunnel; the results showed that after CFTs, the water absorption of PU increased

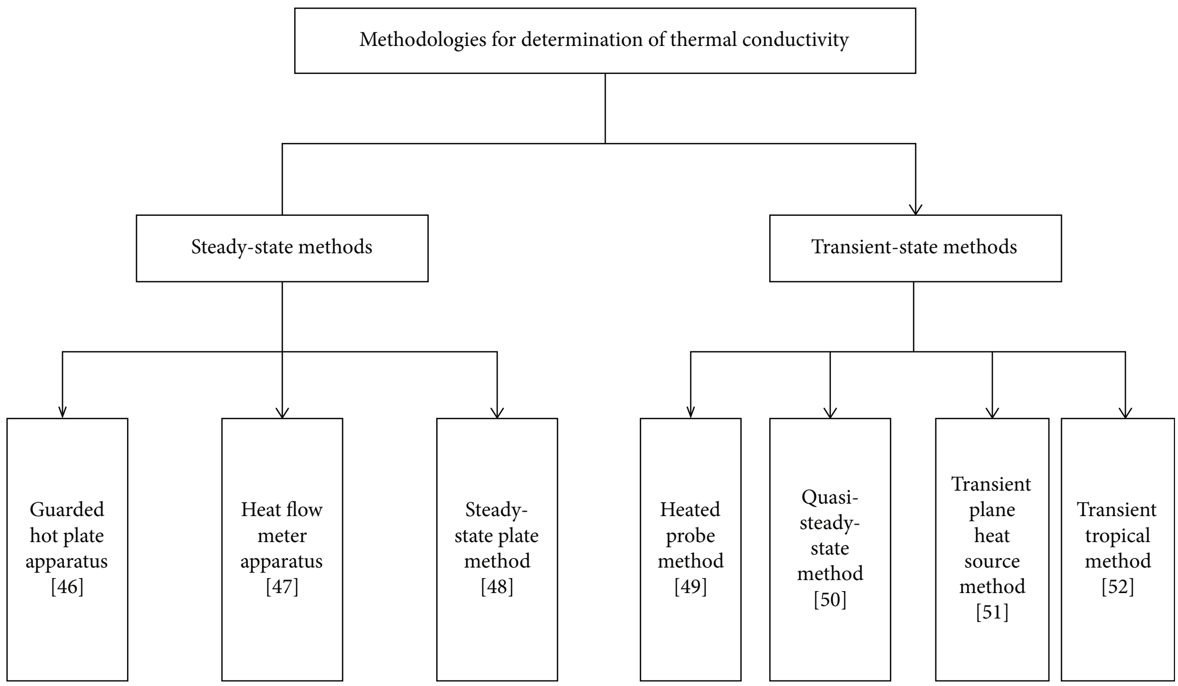

Figure 3: Methodologies for determination of thermal conductivity [46–52].

significantly; meanwhile, the more the initial water content of specimens, the greater the increase. After a fully immersion process and without drainage, the water absorption of PU increased to as much as 700% after 500 FTCs [26]. In the study of Yang [44], changes of water absorption of PF and PU after CFTs following diffusion and immersion process were tested. The results showed that the water absorption of PF after 50 CFTs increased by 3.7 times in diffusion condition and 2.8 times in immersion condition, while, for PU, the initial water absorption was considerable smaller than that of PF. After CFTs, the water absorption did not change considerably in diffusion condition but increased 2 times in immersion condition [44]. Tang et al. tested changes of water absorption of XPS with different apparent densities under CFTs; the results showed that the smaller the apparent density was, the greater the changes of water absorption was with the increase of CFTs [26]. Liu et al. conducted a series of CFT tests on EPS and PU, in which these specimens were immersed in sulfate solution before freezing. The results showed that the effects of sulfate solution concentration on changes of water absorptions of PU were not significant, while for EPS, changes of water absorption were greater when the sulfate solution concentration was 2% [45].

3.2. Thermal Conductivity. Thermal conductivity of TIMs is the most important thermal parameter that determines the engineering application and long-term performance of TIMs. TIMs generally slow the heat transfer by interfering heat conduction and convection. Firstly, TIMs are generally low-thermal conductivity materials. Then, they need to reduce heat conduction through arranging difficult thermal paths for energy flow [5, 13]. Thirdly, they should restrict heat convection as much as possible, because air within the cell structure or fiber matrix will allow energy flow from one air molecule to the other when they collide or by forming convection cells. Compared with conduction, convection is generally a faster heat transfer mode and would cause the increase of the thermal conductivity of materials. The thermal conductivity of TIMs is generally determined by two methodologies in the laboratory, i.e., steady-state methods and transient-state methods (Figure 3). The former one measures thermal properties by establishing a temperature difference which remains constant with time, when the incoming heat is equal to the outgoing heat in the heat transfer process of the system; based on Fourier's law, the thermal conductivity of TIMs can be calculated by testing the temperature gradient on the upper and lower surfaces of samples and the heat flux on a certain heat transfer area. For the latter one, internal temperature of samples can change with time when samples in thermal equilibrium is subjected to local interference, and then, thermal diffusion coefficient is determined by recording the change rate of temperature with time; then, the thermal conductivity of TIMs can be determined based on the differential equation of unsteady heat conduction [44].

Factors affecting the thermal conductivity of TIMs include material composition and structure, apparent density, pore size, sealing degree of cells, temperature, humidity, and heat flow direction [9]. Thus, in the period of use, the thermal conductivity of TIMs is generally not constant. Changes of the thermal conductivity of TIMs induced by CFTs were widely carried out on foam insulation materials. Zhao et al. [53] tested thermal conductivity of EPS and XPS used for channels in cold regions. The results showed that, after experiencing 300 CFTs, their thermal conductivity increased by 70~90% [53]. In the study by Li et al., the test results showed that the thermal conductivity of XPS and PU increased by 5.7% and 26.7%, respectively, after 56 cycles of freezing in a cold chamber (−20°C) for 12 hours and thawing in a constant temperature (20°C) and humidity chamber for 12 hours [54]. Yang [44] compared changes of thermal conductivity of PU and PF when exposed to CFTs. The results showed that the thermal conductivity of PF increased by approximately 2.2 times after 50 CFTs, while that of PU increased by about 22% [44].

Guo [55] carried out tests on freeze-thaw resistance of the silicon polystyrene board. The results demonstrated that after 50 CFTs, the board's thermal conductivity increased by 124% when it was submerged in water for 4 hours prior to the CFT test and by 44.85% when waterproof was utilized [55]. In the study by Gao and Zhang, the test results showed that the thermal conductivity of the polyurethane foam, aluminum silicate ceramics, aluminum foil glass wool, rubber plastic insulation board, and extruded polystyrene board increased by 81.25%, 57.78%, 28.95%, 34.48%, and 32.26%, respectively, after 20 CFTs [56]. In these studies, thermal conductivity of these TIMs was typically measured at a given temperature, such as the standard specified room temperature. In Berardi [15], changes of thermal conductivity of PU and PI foam insulation materials at different temperatures after CFTs were studied systematically, the temperatures ranged from −15 to 25°C, and the results showed that the open-cell PU had a nice performance in freeze-thaw resistance than closed-cell PU, while for PI, the effects of CFTs were significant at cold temperatures [15].

Belayachi et al. [14] tested changes of thermal conductivity of gypsum plaster-straw materials when materials were exposed to CFTs. The test results showed that, compared with drying-wetting cycles, the CFT had no obvious effect on the thermal conductivity of composites [14]. In the study by Lakatos, the thermal performance of glass fibrous-reinforced aerogel samples after CFTs was tested; the results showed that, after long-term freezing, the thermal conductivity of samples remained constant [57]. Berardi and Nosrati [58] conducted different laboratory aging tests to investigate long-term thermal conductivity of aerogel-enhanced insulating materials, including aerogel-enhanced plasters, blankets, and fiberboards. The laboratory tests showed that, after an equivalency of 20 years of aging of CFTs, increases in the thermal conductivity of aerogel-based plasters and aerogel-based gypsum boards were only 2.8% and 3.8%, while for aerogel-enhanced blankets and fiberboards, CFTs had no significant impact on thermal performance of relative TIMs [58]. The two studies above confirmed that when exposed to CFTs, the long-term thermal performance of aerogel-enhanced TIMs was superior to that of conventional TIMs.

For thermal insulation concretes, Yang tests changes of thermal conductivity of foam concretes with admixtures of fly ash, silica, and metakaolin under CFTs and the results showed that the thermal conductivity of these thermal insulation concrete increased by 6.6 to 10.2% after 120 CFTs [59].

4. Changes in Mechanical Properties of TIMs under CFTs

4.1. Compression Strength. Compression strength is an important mechanical parameter of TIMs used in cold regions engineering. Take highway embankment in cold regions as an example; the organic TIMs including XPS, EPS, and PU are typically buried at the bottom of embankment. Thus, TIMs are in a compressed state induced by the weight of overlying fillings and the traffic load. If TIMs are crushed or damaged under the compression, their thermal insulation effect will be decreased, and then, frost heaving and thaw settlement of the embankment will occur.

In the study by Zhao, the changes in compression strength of XPS and EPS used in the seasonal frost region in northeast China were tested and the results showed that the compression strength decreased by about 17% after 30 CFTs [60]. In Liu et al. [45], specimens of EPS and PU were subjected to CFTs after immersed in sodium sulfate solutions of different concentrations (0%, 2%, 4%, and 6%). The compression test results were very dispersive; no obvious decrease trend of the compression strength with the increase of CFTs can be identified, while, for PU, the compression strength seemed to increase slightly after exposure to CFTs. Meanwhile, the effect of the concentration of sodium sulfate solution on the compressive strength of TIMs was not obvious [45].

According to Wang et al. [39], the compression strength of XPS decreased almost linearly with the increasing CFTs. After 200 CFTs, the compression strength of XPS decreased by 32% [39]. In the study by Yang [44], the compression strength of PU and PF was tested when materials were subjected to CFTs after water absorption and immersion. The results showed that, for PU, the compression strength almost did not decrease when PU experienced more than 50 CFTs both after moisture absorption and immersion, while for PF, the 50 CFTs after moisture absorption also did not exert considerable impact on its compression strength but the 50 CFTs after being immersed in water could result in a 12% decrease of compression strength [44]. According to Tang et al., the same conclusion was found for PU when exposed to CFTs after being immersed in water [26]. According to Wang and Zhang, the compression strengths of EPS, PU, rock wool, and XPS decreased by 36%, 38%, 16%, and 20%, respectively, after experiencing 30 CFTs [61]. Therefore, the above studies showed that CFTs could make the compressive strength of traditional TIM decrease.

Foam concrete refers to a type of low-density concrete; it has favorable insulation and thermal performance due to the increase in pores. Thus, in cold regions, foam concrete was widely used as roadbed fillings and void filling materials. Gencel et al. [62] conducted freeze-thaw assessment on basalt fiber-reinforced foam concrete containing silica. The assessment showed that, after CFTs, most mixes experienced higher compression strengths after CFTs [62], while, according to Gong and Zhang [63], the compression strength of the foam concretes with slag powder and silica fume exposed to CFTs was tested; the results showed that the strength loss was considerable. After 25 CFTs, the compression strength loss reached 17% when the silica fume content is 10% [63]. Ferrándiz-Mas and García-Alcocel [64] investigated the durability of expanded polystyrene mortars under CFTs. The results showed that the compression strength of mortars subjected to CFTs was improved after adding expanded polystyrene particles [64].

4.2. Tensile and Shear Strength. Tensile strength of TIMs refers to the maximum tensile stress when they are destroyed under uniaxial tension. The previous research showed that CFTs have negative effects on the tensile strength of TIMs, but to varying degrees. In the study by Xu, the tensile strength of rock wool, XPS, and TDF board decreased 66.7%, 66.7%, and 42.85%, respectively, after 40 CFTs [65]. In the study by Zhang et al., the test results showed that the reduction of bond strength of PU thermal insulation systems was the largest after and that of molding board was the minimum after 10 CFTs [66]. Yin [67] studied the changes of tensile force of XPS, PU, and silicon polystyrene under 10, 20, and 30 CFTs, respectively. The results showed that, after 30 CFTs, the declines of tensile force of XPS, PU, and silicon board were 66.39%, 55.38%, and 34.99%, respectively [67]. According to Hua, after 30 CFTs, the declines of tensile strength of the thermosetting composite polystyrene foam insulation board (TEPS) and cement-based thermal insulation board were about 40% [68]. Yan [69] analyzed the attenuation curves of tensile bond strength of LS-1, LS-2, and grooved-type composite insulation board after CFTs. He found that these curves could be divided in three stages, including slow, fast, and steady decline stages of tensile strength. Meanwhile, he found that the greater water absorption and longer freezing time could cause worse freeze-thaw resistance of TIMs; meanwhile, grooves as well as the protected layer can improve their durability [69].

Shear strength of TIMs refers to the maximum shear stress when they are subjected to shear force. When TIMs are laid on the outer surface of buildings, their self-weight can cause vertical shear stress, this shear stress increases with the increase of the area of TIMs and building outer facing tiles. In cold regions, shear strength of TIMs in the outer layer of buildings can change with CFTs, which can cause the risk of falling off and breaking of TIMs. Therefore, it is necessary to evaluate the impact of CFTs on the shear strength of TIMs. According to Xu, after 40 CFTs, the shear strength of rock wool, XPS, and TDF board (TDF is a kind of waterproofing agent) decreased with the increase of CFTs but the shear strength of the TDF board is larger than that of rook wool and XPS [65]. According to Yin, after 30 CFTs, the shear strength decrease of XPS and PU was basically 22.86% and the decrease in the shear strength of silicon polystyrene was 7.94% [67].

5. Changes in Deformation Properties of TIMs under CFTs

Dynamic elastic modulus and elastic modulus refer to the ability of materials to resist deformation when they are loaded; the former can be measured by sound speed and affected by the loading rate. The latter can be measured by uniaxial compression experiment. According to Yang et al., after 50 CFTs, the elastic modulus of the glazed hollow bead thermal insulation mortar decreased by 20%, which showed that CFTs caused irreversible strain to the mortar [70]. Niu et al. [25] measured the elastic modulus of four kinds of XPS with different apparent densities, including FM200 ($30.75\,g{\bullet}cm^{-3}$), FM700 ($52.10\,g{\bullet}cm^{-3}$), SP350 ($33.40\,g{\bullet}cm^{-3}$), and LB ($32.64\,g{\bullet}cm^{-3}$). The results showed that the Yong's modulus was reduced by 5.35%, 2.83%, 9.14%, and 6.53% (FM200, FM700, SP350, and LB, respectively) after 50 CFTs, while the reduction rate of Young's modulus was 6.49%, 3.27%, 9.64%, and 7.48% for the XPS subjected to 400 times CFTs [25].

The rheological properties of TIMs refer to the change law of the stress-strain state of TIMs with time under the action of external force. Creep is a kind of rheological properties; it refers the changes of strain of TIMs with time when the stress is constant. Generally, the load process of road, traffic load, and the loading process of tunnel wall surrounding rock will lead to the creep of TIMs. The creep strain types can be divided into the decay creep and undecay creep due to different stress [71]. For embankments, the vertical deformation caused by the creep was up to 0.2% of the total strain; after more than a year, the creep of EPS20 amounts to 0.2%; within the first day, over half of the maximum anticipated creep in the EPS was already present [70]. According to Zhao et al., the creep properties of EPS, XPS, and ethylene vinyl acetate copolymer (EVA) were well in dry condition but the change of creep deformation of EVA was larger than that of EPS and XPS when these materials were immersed in water [53]. According to Niu et al., the creep strain of XPS is the decay creep [25].

6. Changes in the Microstructure of TIMs under CFTs

According to Ostrogorsky et al., the first microscopic analysis of the foam cellular microstructure was performed in the 1980s to observe the cellular structure of PU [72]. Liu [73] observed the scanning electron microscope (SEM) image of the interface between EPS and inorganic matrix in the TIMs. After 10 CFTs, they found that there were some cracks in the matrix and the interface between EPS and inorganic was separated [73]. In Tang, the SEM images of the inorganic insulation mortar with different ratios of aggregate and powder as well as water repellent after CFTs were observed; the results showed that the cracks in the pores and acicular crystals near the pores of the mortar increased after CFTs; meanwhile, the size of pores was increasing [74]. In the study by Yang, almost all closed pores in FLK were destroyed after 50 CFTs; however, compared with FLK, PU had better freeze-thaw resistance than FLK [44]. In the study by Berardi and Madzareaic, PU and PI were observed by SEM; in comparison to closed-cell foams of PI and PU, the open-cell foams of PU looked translucent on the 130 scale; closed-cell foams of PI and PU with oven aged foams have reduced aspect ratios compared to their not aged of CFTs samples, and the cell walls of open cell foams of PU, are less opaque than the cell walls of the closed cell foams [75].

7. Conclusions

The status and progress of the test apparatus, temperature controls of the CFT test, and the changes of thermal and mechanical properties of TIMs under the CFT actions were summarized based on a systematic literature review. From the summary, it can be found that, compared with concrete and soil, impacts of CFTs on physical and mechanical properties of TIMs were not evaluated well at present. There are so many differences in test methods of CFTs on the TIMs. These differences are related not only to the material composition of TIMs but also to their manufacturing technique and working environment.

Because of the difference test methods, the results in previous research were very sparse, which is not beneficial for engineering application and improvement of TIMs. Along with extensive use of TIMs in cold regions, a unified test method for the durability of TIMs under CFTs should be established in the future. Compared with their physical properties, the mechanical property changes of TIMs under CFTs still need more attention. Meanwhile, there are so many kinds of TIMs in the market but their properties were not well summarized and compared under CFT actions. So, it is necessary to establish the database on the properties of TIMs and improve the classification of TIMs based on these properties.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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