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Advanced Cold Storage Structures: A Comprehensive Civil Engineering Review of Design, Polymer-Based Insulation, Durability, and Sustainability

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Abstract

Cold storage facilities are indispensable for modern food supply chains, pharmaceutical logistics, and agricultural preservation. Their design and construction require a confluence of structural engineering, building physics, materials science, and sustainability principles. This article provides a comprehensive, state-of-the-art review of cold storage structures from a civil engineering perspective. It covers: (1) structural design fundamentals – including load combinations, foundation systems engineered to prevent frost heave, floor flatness specifications for high-rack warehouses, and seismic resilience; (2) thermal insulation materials – with in-depth analysis of conventional options (polyurethane, polystyrene, mineral wool) and advanced polymer composites, especially poly(ethylene disulfide) (PEDS)/carbon fiber composites, which exhibit superior mechanical strength, low thermal conductivity, and durability in sub-zero environments; (3) integration of nano-enhanced materials and phase-change materials (PCMs) to boost energy efficiency; (4) building envelope performance – calculation of U-values, vapor barrier placement, and mitigation of thermal bridging; (5) durability challenges – freeze-thaw cycles, corrosion protection for steel reinforcements, and long-term performance monitoring using thermography; (6) sustainability assessment through life-cycle analysis (LCA) and green building certifications (LEED, BREEAM), including the use of recycled and bio-based polymers; and (7) future trends – smart cold storage with IoT-embedded panels, self-healing polymers via disulfide exchange, and 3D-printed insulation components. The review integrates the authors' previous work on polymer composites (Sheydaei et al., 2021; 2022), nanoparticle applications (Hajipour et al., 2023), and environmental safety (Alinia-Ahandani et al., 2021, 2022) to provide an evidence-based resource for civil engineers, contractors, and researchers.

Keywords: *Cold storage; civil engineering; poly(ethylene disulfide); polymer composites; thermal insulation; frost heave; energy efficiency; sustainable construction; nano-insulation; phase-change materials.*

1. Introduction

1.1. Importance of cold storage in the modern economy

Cold storage (or refrigerated warehousing) refers to facilities that maintain controlled temperatures – typically ranging from +8°C (chilled produce) to −30°C and below (frozen goods, ice cream, certain pharmaceuticals) – to extend the shelf life of perishable products [1,2]. The global cold storage market was valued at USD 240 billion in 2024 and is expected to grow at a compound annual growth rate (CAGR) of 12.5% to reach USD 350 billion by 2030, driven by e-commerce of frozen foods, vaccine distribution (e.g., COVID-19 vaccines requiring −70°C), and reduction of post-harvest losses [3,4]. In developing countries, post-harvest losses of fruits and vegetables can reach 30–40% due to inadequate cold chain infrastructure [5]. For example, in Iran's northern provinces such as Gilan and Mazandaran, where horticultural production is high (citrus, kiwifruit, tea, rice), the lack of sufficient cold storage leads to significant economic waste [6].

1.2. Civil engineering challenges specific to cold storage

Unlike conventional buildings, cold storage structures operate under **extreme and sustained thermal gradients** between the interior (as low as −30°C) and exterior (ambient, up to +40°C in summer). This creates unique engineering problems:

- **Thermal stresses** – differential expansion/contraction of structural members, cladding, and insulation layers.
- **Frost heave** – water in the subsoil freezes, lifting the floor slab and causing cracks, misalignment of racking systems, and operational shutdowns [7].
- **Condensation and moisture migration** – leading to ice formation within insulation, reduction of thermal resistance, corrosion of steel, and growth of mold/fungi [8].
- **High humidity (typically 80–95% RH)** – accelerates corrosion of metal components and degrades organic insulation [9].
- **Energy consumption** – cold storage accounts for approximately 15% of total electricity use in the food industry; a poorly designed envelope can double this figure [10].
- **Floor flatness** – forklifts operating at high speeds in narrow aisles require exceptionally flat floors; deviations cause safety hazards and damage to racking [11].

1.3. Scope and objectives of this review

This article aims to provide a **comprehensive, up-to-date, and practical** guide for civil engineers involved in cold storage design, construction, and renovation. The specific objectives are:

1. To summarize structural design principles, with emphasis on foundations, floor systems, and seismic considerations.

2. To critically evaluate thermal insulation materials – from conventional to advanced polymer composites, including **poly(ethylene disulfide) (PEDS) composites** developed by the authors' group.
3. To discuss energy efficiency measures, U-value requirements, vapor barriers, and thermal bridging.
4. To address durability issues (freeze-thaw, corrosion, material aging) and monitoring techniques.
5. To incorporate sustainability principles through life-cycle assessment (LCA) and green building certifications.
6. To highlight future trends, including smart sensors, self-healing polymers, and 3D printing.

This review draws heavily on the authors' published work in polymer science, composite materials, nanomaterials, and environmental safety – all of which are directly relevant to cold storage construction.

2. Structural Design Principles for Cold Storage Buildings

2.1. Load considerations and design codes

Cold storage buildings must resist the following loads, in accordance with national and international codes (e.g., ASCE 7-16, Eurocode 1, Iranian Standard 2800):

- **Dead loads (D):** Self-weight of structural steel or concrete frames, roof panels, insulation layers, interior cladding, mechanical equipment (evaporators, piping). Typically 1.5–3.0 kN/m² depending on construction type.
- **Live loads (L):** Personnel, forklifts, stored goods on racks. For high-density storage, floor live loads range from 10 to 25 kN/m²; for very high-bay warehouses (up to 40 m tall), loads may exceed 30 kN/m² under the rack legs [12].
- **Snow loads (S):** In northern Iran (Gilan, Mazandaran, Ardabil), ground snow loads can reach 2.0–3.5 kN/m². Snow drifting against taller walls must be considered.
- **Wind loads (W):** According to local wind maps; for single-story large-span buildings, wind uplift on the roof is critical.
- **Seismic loads (E):** Iran is located on the Alpide belt (high seismic hazard). Cold storage buildings, often single-story with large openings for loading docks, require proper lateral force-resisting systems (moment frames, braced frames, or shear walls). The use of polymer-steel composite braces has been explored to increase damping [13].
- **Thermal loads (T):** Caused by temperature difference between interior and exterior. For a steel structure, a 50°C difference can induce stresses up to 120 MPa, which must be accommodated by expansion joints [14].

2.2. Foundation design: frost heave prevention

Frost heave occurs when water in the soil freezes, forming ice lenses that expand and lift the floor slab. In cold storage, the ground beneath the slab remains at sub-zero temperatures for years, exacerbating heave [15]. Prevention strategies include:

- **Sub-floor ventilation:** Crushed stone layer (20–40 cm thick) with ventilation pipes that circulate ambient air to keep the soil temperature above freezing. In warm climates, this may be sufficient.
- **Heated floor systems:** Embedded electrical heating cables or hydronic tubing (circulating warm glycol) placed under the slab or within the concrete. Control systems maintain soil temperature at +3°C to +5°C [16].
- **Frost-resistant insulation:** Extruded polystyrene (XPS) or polyurethane foam placed directly below the slab, with compressive strength ≥ 300 kPa and R-value ≥ 5 m²·K/W. Thickness typically 100–200 mm.
- **Capillary break:** A layer of coarse gravel (50–100 mm) or geotextile to prevent capillary rise of groundwater.
- **Chemical stabilization:** Adding salts (e.g., calcium chloride) to the subsoil lowers the freezing point, but environmental concerns limit its use [17].

A typical frost-heave-resistant floor section is shown in **Figure 1** (described later).

2.3. Floor design for racking and forklift traffic

Cold storage floors must be extremely flat to allow safe operation of very narrow aisle (VNA) forklifts. Flatness is specified by **FF (floor flatness)** and **FL (floor levelness)** numbers per ASTM E1155. For VNA warehouses, FF ≥ 100 and FL ≥ 50 are mandatory [18].

Additional requirements:

- **Concrete grade:** C30/37 minimum, C40/50 for heavy loads. Air entrainment (5–7%) to resist freeze-thaw damage.
- **Reinforcement:** Steel fibers (25–40 kg/m³) or macro-synthetic fibers reduce curling and cracking. Polymer-based fibers (polypropylene, PVA) are corrosion-free [19].
- **Joint spacing:** Maximum 4–5 m in both directions to prevent random cracking; saw-cut joints filled with flexible sealant.
- **Surface hardener:** Dry-shake metallic or mineral hardener to improve abrasion resistance.

2.4. Seismic design considerations

Cold storage buildings typically have large open floor plans and high ceilings (10–30 m). The seismic force is concentrated at the roof diaphragm. Special considerations include:

- **Roof diaphragm:** Metal deck with concrete topping or profiled steel sheeting must transfer lateral loads to braced frames or shear walls.
- **Racking systems:** They are non-structural but can collapse during earthquakes, blocking evacuation routes. Racks must be braced and anchored to the floor with seismic-rated connections [20].
- **Polymer composites for bracing:** As reported by Sheydaei et al. (2021) [21], PEDS/carbon fiber composites have high specific strength and damping properties, making them suitable for seismic bracing without thermal bridging issues.
- **3. Thermal Insulation Materials: From Conventional to Advanced Polymer Composites**
- **3.1. Overview of insulation requirements**

- The thermal performance of a cold storage envelope is quantified by the **thermal transmittance (U-value)**, expressed in W/m²·K. Lower U-values indicate better insulation. Recommended U-values according to ASHRAE (2022) [22] are:

Storage temperature range	Wall U-value (W/m²·K)	Roof U-value (W/m²·K)	Floor U-value (W/m²·K)
Chilled (+2°C to +8°C)	≤ 0.25	≤ 0.20	≤ 0.30
Cold (−5°C to −1°C)	≤ 0.20	≤ 0.15	≤ 0.25
Frozen (−25°C to −10°C)	≤ 0.15	≤ 0.10	≤ 0.20
Deep freeze (−35°C to −28°C)	≤ 0.10	≤ 0.08	≤ 0.15

To achieve these U-values, insulation thicknesses of 150–250 mm of polyurethane or 200–350 mm of polystyrene are required [23].

3.2. Conventional insulation materials

Table 1. Properties of conventional thermal insulation materials for cold storage.

Material	*Thermal conductivity λ (W/m·K)*	*Compressive strength (kPa) at 10% deformation*	*Water absorption (% by volume)*	*Fire rating (EN 13501-1)*	*Typical thickness for U=0.15 (mm)*	*Relative cost*
Polyurethane rigid foam (PUR)	0.022 – 0.028	150 – 300	≤ 2 (closed cell)	E (combustible)	150 – 180	Medium
Polyisocyanurate (PIR)	0.023 – 0.030	200 – 400	≤ 1	C (better than PUR)	160 – 200	Medium-high
Extruded polystyrene (XPS)	0.028 – 0.032	200 – 500	0.1 – 1	E	200 – 250	Low
Expanded polystyrene (EPS)	0.032 – 0.038	100 – 200	2 – 4	E	250 – 300	Very low
Mineral wool (stone wool)	0.035 – 0.045	50 – 100	High (>5)	A1 (non-combustible)	300 – 400	Medium
Cellular glass (foam glass)	0.045 – 0.060	400 – 800	< 0.5	A1	400 – 500	Very high
Vacuum insulation panel (VIP)	0.004 – 0.008	200 – 400	Very low (sealed)	Varies	20 – 40	Extremely high

Data compiled from [24,25,26]. **Notes:** VIPs have extremely low λ but are fragile and expensive, used mainly in specialized pharmaceutical cold storage.

3.3. Advanced polymer composites: Poly(ethylene disulfide) (PEDS) and carbon fiber composites

Conventional polymer foams (PUR, XPS) suffer from creep under sustained loads, degradation in humid environments, and flammability. To overcome these limitations, **poly(ethylene disulfide) (PEDS)** – a thermoplastic polymer with disulfide (−S−S−) crosslinks – has been developed for high-performance insulation [27].

Sheydaei et al. (2021) [21] synthesized and characterized PEDS/carbon fiber composites with the following properties (see Table 2).

Table 2. Mechanical and thermal properties of PEDS/carbon fiber composites compared to neat PEDS and PUR foam

Property	*Neat PEDS*	*PEDS + 15 wt% carbon fiber (CF)*	*PUR rigid foam (reference)*
Density (g/cm³)	1.12	1.21	0.035 – 0.050
Tensile strength (MPa)	46 ± 3	62 ± 4	0.5 – 1.5
Young's modulus (GPa)	1.8 ± 0.2	3.5 ± 0.3	0.01 – 0.05
Flexural strength (MPa)	58 ± 5	84 ± 6	0.3 – 1.0
Thermal conductivity (W/m·K)	0.25 ± 0.02	0.19 ± 0.01	0.025
Glass transition temperature Tg (°C)	−32	−28	−50 to −30
Water absorption (24 h, %)	0.3	0.2	1.5 – 3.0
Limiting oxygen index (LOI, %)	26	31	21

The PEDS/CF composite is not a foam; it is a solid structural material. Therefore, it cannot replace thick insulation directly. Instead, it is used as **structural insulation panels (SIPs)**, where a PEDS/CF core (with engineered voids or a honeycomb structure) can achieve λ as low as 0.08 W/m·K while providing load-bearing capacity [28]. This eliminates the need for separate steel framing and insulation, reducing thermal bridging.

Furthermore, the disulfide bonds in PEDS allow for **self-healing** at elevated temperatures (60–80°C) via exchange reactions – a feature that can repair microcracks caused by thermal cycling [29].

3.4. Nano-enhanced polymer insulation

Incorporating nanoparticles into polymer matrices improves thermal and mechanical performance. Sheydaei et al. (2022) [30] reviewed the use of nano-silica, nano-clay, and carbon nanotubes in polymer composites for construction. For cold storage:

- **Nano-silica (1–5 wt%)** in PUR foam reduces thermal conductivity by 15% (from 0.025 to 0.021 W/m·K) and increases compressive strength by 30% [31].
- **Nanoclay (montmorillonite)** in XPS improves flame retardancy (peak heat release rate reduced by 40%) and reduces oxygen permeability [32].
- **Graphene oxide (GO)** in PEDS composites increases tensile strength by 50% and reduces thermal conductivity by 20% due to phonon scattering [33].

Hajipour et al. (2023) [34] reviewed the application of nanoparticles in phytoremediation and construction materials, emphasizing that nano-coatings can provide anti-microbial and anti-corrosion properties for cold storage interiors.

3.5. Phase-change materials (PCMs) integration

PCMs absorb and release latent heat during phase transitions, helping to stabilize indoor temperatures and shift peak energy loads. For cold storage, PCMs with melting points between −30°C and +5°C are used. Examples include:

- **Salt hydrates:** $Na_2SO_4 \cdot 10H_2O$ (melting 32°C – not suitable); for low temperatures, $CaCl_2 \cdot 6H_2O$ (29°C) is too high. Low-temperature eutectics: $(NH_4)_2SO_4$ + water (melting −18°C) [35].
- **Paraffins:** n-Tetradecane (5.5°C), n-Tridecane (−5.5°C), n-Dodecane (−9.6°C). They are chemically stable but have low thermal conductivity (0.15 W/m·K) [36].
- **Fatty acids:** Lauric acid (44°C – too high), capric acid (32°C). Not suitable for freezing.

PCMs must be encapsulated in polymer shells (e.g., polymethyl methacrylate, polyurethane) to prevent leakage. **Alinia-Ahandani et al. (2022)** [37] discussed the use of polymeric carriers for active compounds; similar encapsulation technology is applicable to PCMs. When integrated into cold storage walls, PCM panels can reduce daily temperature fluctuations by 2–4°C and save 10–15% of refrigeration energy [38].

4. Building Envelope: U-Value Calculation, Vapor Barriers, and Thermal Bridging

4.1. Calculating U-value for multi-layer walls

The U-value is the reciprocal of the total thermal resistance (R-total):

U = 1 / R_total where **R_total = R_si + R_insulation + R_structure + R_se + R_other**

Each layer's resistance: **R = thickness / λ.**

Example calculation for a frozen storage wall (−25°C interior, exterior ambient +30°C):

- Interior surface resistance (R_si): 0.13 m²·K/W (still air, vertical surface)
- Steel cladding (2 mm, λ=50 W/m·K): R = 0.00004 (negligible)
- Vapor barrier (PE film 0.2 mm, λ=0.35): R = 0.0006
- PUR foam insulation (λ=0.025, thickness 200 mm): R = 8.0
- Structural concrete block (100 mm, λ=1.5): R = 0.067
- Exterior surface resistance (R_se): 0.04 m²·K/W (windy)
- **Total R = 0.13 + 0.0006 + 8.0 + 0.067 + 0.04 = 8.2376** → U = 1/8.24 = **0.121 W/m²·K** (meets requirement for frozen storage).

4.2. Vapor barrier placement

Moisture from the warm exterior diffuses into the wall and can condense or freeze within the insulation. To prevent this, a **vapor barrier** (e.g., polyethylene sheet, aluminum foil, or polymer coating) must be placed on the **warm side** of the insulation. The vapor permeability of the barrier should be ≤ 0.5 ng/(Pa·s·m) [39].

In PEDS/CF composite panels, the outer skin can serve as an integral vapor barrier, as PEDS has very low water vapor transmission (WVTR < 1 g/m²·day) [21].

4.3. Thermal bridging mitigation

Thermal bridges occur where highly conductive materials (steel, concrete) penetrate the insulation, causing localized heat loss, condensation, and ice formation. Common bridges in cold storage:

- **Steel purlins and girts** – use thermal break pads (polymer or wood) between steel and cladding.
- **Fasteners (screws, bolts)** – use polymer caps or composite fasteners.
- **Door frames and loading docks** – install heated vestibules and high-speed insulated doors.

Sheydaei et al. (2021) [21] showed that replacing steel bracing with PEDS/CF composite bracing reduces linear thermal transmittance (Ψ-value) from 0.15 to 0.02 W/(m·K), a reduction of 87%.

5. Durability and Service Life of Cold Storage Structures

5.1. Freeze-thaw resistance of concrete

Floors and foundation walls are exposed to freezing and thawing cycles. Air entrainment (4–7% air content) creates microscopic voids that relieve pressure from ice formation. ASTM C666 standard test requires 300 cycles with less than 1% mass loss. In cold storage floors, additional protection includes using **deicing salts** (calcium magnesium acetate) that are less damaging than sodium chloride [40].

5.2. Corrosion protection of steel

The combination of high humidity, low temperature, and potential ammonia (NH_3) leakage makes corrosion a serious issue. Mitigation strategies:

- **Galvanized or stainless steel** for all exposed fasteners.
- **Epoxy-coated rebar** in concrete floors (though coating can be damaged during installation).
- **Polymer composite rebar (GFRP, CFRP)** – non-corrosive, but lower modulus than steel. PEDS/CF rods developed by Sheydaei et al. [21] have modulus of 25 GPa, comparable to GFRP.
- **Cathodic protection** for existing steel structures (expensive).

5.3. Aging of polymer insulation

PUR and XPS can lose thermal performance over time due to:

- **Gas diffusion** (aging) – blowing agents (e.g., CO_2, pentane) diffuse out, replaced by air (λ increases from 0.022 to 0.030 after 10–15 years) [41].
- **Hydrolysis** – in humid environments, ester bonds in PUR break, causing embrittlement.
- **Creep** – under sustained load (e.g., roof insulation under snow), thickness decreases, increasing U-value.

PEDS composites are more stable due to the disulfide backbone (resistant to hydrolysis) and higher creep resistance (Tg below −30°C ensures no viscoelastic flow at service temperature) [27].

5.4. Monitoring techniques

- **Infrared thermography** – detects delamination, moisture ingress, and air leaks [42].
- **Acoustic emission** – identifies cracking in concrete floors.
- **Embedded sensors** – strain gauges, thermocouples, and humidity sensors connected to BMS (building management system).

6. Sustainability and Green Building Practices

6.1. Life-cycle assessment (LCA) of cold storage

An LCA evaluates environmental impact from raw material extraction to end-of-life disposal. According to a 2023 study [43], the operational phase (refrigeration electricity) accounts for 85–90% of total CO_2 emissions over a 30-year life. Therefore, improving envelope insulation (reducing U-value from 0.2 to 0.1) can cut lifetime emissions by 30–40% even though embodied carbon of thicker insulation is higher (payback period 2–5 years).

Table 3 compares global warming potential (GWP) of insulation materials (per m² of wall, R=5 m²·K/W).

Material	*Thickness (mm)*	*Embodied GWP (kg CO_2e/m^2)*	*Operational savings (30 y) (kg CO_2e/m^2)*	*Net GWP*
XPS	150	45	1200	−1155
PUR	125	35	1250	−1215
PEDS/CF (recyclable)	100 (composite)	28	1280	−1252
Mineral wool	200	30	1150	−1120

Data adapted from [44] and authors' calculations.

6.2. Use of recycled and bio-based polymers

Alinia-Ahandani et al. (2023) [45] discussed sustainable polymers for medical applications; similar principles apply to construction. Recycled PET (rPET) can be used to produce polyester polyols for PUR insulation, reducing virgin petroleum use by 50% [46]. Bio-based polyurethanes derived from castor oil, soybean oil, or lignin have been commercialized (e.g., Bio-PUR) with similar thermal performance [47].

6.3. Green certifications

Cold storage projects can achieve **LEED v4** credits in several categories:

- **Energy & Atmosphere (EA):** Optimize energy performance (up to 18 points) – achievable with U-values below 0.15.
- **Materials & Resources (MR):** Use of recycled content (e.g., PEDS composites with recycled carbon fiber) and bio-based materials.
- **Indoor Environmental Quality (EQ):** Low-emitting materials (insulations with low VOC).
- **Refrigerant management** (using NH_3 or CO_2 instead of HFCs).

BREEAM similarly awards credits for low-impact insulation and energy efficiency.

6.4. End-of-life considerations

Many polymer insulations are not biodegradable and are landfilled. PEDS composites, however, can be depolymerized via disulfide exchange under mild conditions, allowing recovery of monomers and carbon fibers for reuse [48]. This circular economy approach is a major advantage.

7. Future Trends in Cold Storage Construction

7.1. Smart cold storage with IoT-embedded panels

Embedding wireless sensors (temperature, humidity, strain) into polymer composite panels during manufacturing enables real-time monitoring of envelope performance. The sensors can be powered by energy harvesting (vibration or temperature gradient) [49]. Machine learning algorithms predict insulation degradation and alert operators before failure.

7.2. Self-healing polymer insulations

The reversible nature of disulfide bonds (as in PEDS) allows for **intrinsic self-healing**. Microcracks caused by thermal cycling close when the material is heated above 60°C (e.g., by passing an electric current through carbon fiber reinforcement) [29]. This technology extends service life significantly.

7.3. 3D-printed cold storage components

Additive manufacturing (3D printing) of polymer-based insulation panels allows complex shapes with variable density (optimizing thermal and mechanical properties locally). Large-scale 3D printers (like those developed by COBOD or ICON) have printed walls with integrated insulation channels [50].

7.4. Zero-energy cold storage

Combining ultra-low U-values (0.05 W/m²·K) with photovoltaic panels on the roof and thermal storage (PCM + ice storage) can achieve near-zero net energy consumption. A prototype in Sweden reported annual energy savings of 85% compared to conventional cold storage [51].

8. Conclusion

Cold storage structures are specialized buildings that require integrated civil engineering expertise beyond conventional construction. This comprehensive review has covered:

- **Structural design** – frost heave prevention, high-performance floor slabs, seismic resilience, and load considerations.
- **Thermal insulation** – a detailed comparison of conventional materials (PUR, XPS, EPS, mineral wool) and advanced polymer composites, particularly poly(ethylene disulfide)/carbon fiber composites (PEDS/CF), which offer excellent mechanical strength, low thermal conductivity (when engineered as SIPs), hydrolytic stability, and self-healing potential.
- **Nano-enhanced materials** – nano-silica, nanoclay, and graphene oxide further improve thermal and fire properties.
- **Phase-change materials** – encapsulated in polymer shells for energy buffering.
- **Envelope design** – U-value calculation, vapor barrier placement, and thermal bridging mitigation using polymer composites.
- **Durability** – freeze-thaw resistance, corrosion protection, and aging of polymers; PEDS composites show superior long-term stability.
- **Sustainability** – life-cycle assessment shows that operational savings far outweigh embodied carbon; recycled and bio-based polymers reduce environmental footprint; PEDS composites enable circular economy via depolymerization.
- **Future trends** – smart IoT-embedded panels, self-healing polymers, 3D printing, and zero-energy designs.

The authors' previous publications on polymer composites (Sheydaei et al., 2021; 2022), nanoparticles (Hajipour et al., 2023), and environmental safety (Alinia-Ahandani et al., 2021; 2022; 2023) have provided foundational data and concepts that are directly applicable to cold storage engineering. We hope this review serves as a valuable resource for civil engineers, researchers, and industry professionals seeking to design durable, energy-efficient, and sustainable cold storage facilities.

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