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EVALUATING SAFETY FACTORS IN CORRUGATED PACKAGING FOR EXTREME ENVIRONMENTAL CONDITIONS

OCENA CZYNNIKÓW BEZPIECZEŃSTWA OPAKOWAŃ Z TEKTRY FALISTEJ W EKSTREMALNYCH WARUNKACH ŚRODOWISKOWYCH

ABSTRACT: This article presents an in-depth analysis of the critical safety factors necessary for corrugated packaging, particularly in the context of transportation and storage under extreme environmental conditions such as high humidity and low temperatures. The study begins with an overview of the fundamental properties and applications of corrugated packaging materials, emphasizing their significance in the global supply chain. It then delves into the specific safety factors that are crucial for maintaining the structural integrity of corrugated packaging, including compressive strength, burst strength, and edge crush test ratings. Special attention is given to the impact of extreme environmental conditions on these materials. The article highlights how factors like humidity and temperature fluctuations can significantly weaken corrugated packaging, necessitating adjustments in safety factors. Tables outlining suggested safety factor ranges for various conditions are provided to guide manufacturers and shippers in adapting their packaging strategies. Furthermore, the article reviews relevant ASTM and ISO standards, along with FEFCO guidelines, providing insights into industry best practices and compliance requirements. This comprehensive analysis aims to equip stakeholders in the packaging industry with the knowledge to ensure the durability and reliability of corrugated packaging, thereby safeguarding the quality and safety of goods in transit and storage.

Key words: safety factors, corrugated board, packaging strength

STRESZCZENIE: Artykuł ten przedstawia dogłębną analizę kluczowych czynników bezpieczeństwa niezbędnych dla opakowań z tektury falistej, szczególnie w kontekście transportu i przechowywania w ekstremalnych warunkach środowiskowych, takich jak wysoka wilgotność i niskie temperatury. Badanie rozpoczyna się od przeglądu podstawowych właściwości i zastosowań materiałów do opakowań transportowych, podkreślając ich znaczenie w globalnym łańcuchu dostaw. Następnie zagłębia się w konkretne czynniki bezpieczeństwa, które są kluczowe dla zachowania integralności strukturalnej opakowań falistych, w tym wytrzymałość na ściskanie, wytrzymałość na przebicie i odporność na zgniatanie krawędziowe. Szczególna uwaga poświęcona jest wpływowi ekstremalnych warunków środowiskowych na tekturę falistą. Artykuł podkreśla, jak czynniki takie jak wilgotność i wahania temperatury mogą znacząco osłabić opakowania z tektury falistej, wymagając dostosowania czynników bezpieczeństwa. Zapewnione są tabele z zalecanymi zakresami czynników bezpieczeństwa dla różnych warunków, aby pomóc producentom i nadawcom w dostosowaniu ich strategii opakowaniowych. Ponadto artykuł przegląda odpowiednie normy ASTM i ISO, wraz z wytycznymi FEFCO, dostarczając wglądu w najlepsze praktyki branżowe i wymagania zgodności. To wszechstronne badanie ma na celu wyposażenie interesariuszy branży opakowaniowej w wiedzę, która zapewni trwałość i niezawodność opakowań, chroniąc tym samym jakość i bezpieczeństwo towarów w transporcie i magazynowaniu.

Słowa kluczowe: współczynniki bezpieczeństwa, tektura falista, nośność opakowania

1. INTRODUCTION

In the rapidly evolving landscape of global trade and logistics, corrugated packaging plays a pivotal role in the protection and safe delivery of goods across diverse industries. As the backbone of modern packaging solutions, corrugated materials offer a unique blend of strength [22], flexibility, and sustainability [2, 24, 26], making them an ideal choice for a wide range of

applications. However, the performance of these materials is not immune to the challenges posed by environmental factors. Extreme temperature and humidity conditions [21], commonly encountered during transportation and storage [17, 25], can significantly impact the structural integrity and effectiveness of corrugated packaging.

Transportation and storage of goods involve a myriad of environmental challenges that can significantly affect the integrity and safety of products. Corrugated packaging commonly used for shipping and storing products faces various environmental stressors that necessitate careful consideration in its design and material selection [7, 12, 20]. One of the primary challenges in transportation and storage is temperature fluctuations. Products may be exposed to extreme heat or cold depending on the geographic location and time of year. These temperature variations can affect the physical properties of corrugated packaging materials making them either brittle in cold conditions or overly pliable in hot environments which can lead to structural failures.

Humidity is another critical factor particularly in regions with high moisture levels or during sea transport. Humidity can weaken the corrugated fiberboard reducing its strength and making it more susceptible to damage [3]. Moisture absorption can also lead to mold and mildew growth which not only compromises the structural integrity of the packaging but can also pose health hazards especially for food and pharmaceutical products. Mechanical stresses such as vibrations shocks and impacts during transportation are further challenges [17]. These can occur during handling loading and unloading as well as from the movement of the transportation vehicle itself. These mechanical forces can cause deformation crushing or even bursting of packaging especially if the material is not robust enough to withstand such stress.

Another challenge is exposure to chemicals or contaminants. This can occur during industrial shipments or due to environmental factors such as air pollution or exposure to saltwater during maritime shipping. Such exposure can degrade packaging materials leading to potential contamination of the contents. Overall managing these environmental challenges is crucial for ensuring the safe and effective transport and storage of goods. It requires a thorough understanding of the conditions that the packaging will be exposed to and the selection of appropriate materials and design features that can withstand these challenges. This not only ensures the safety and integrity of the products being transported but also enhances the efficiency and reliability of the supply chain operations.

In recent years the packaging industry has recognized the growing need for estimating the strength of corrugated boxes using simple analytical formulas and numerical methods [4, 8, 10, 13, 18, 2]. This approach is essential for optimizing design ensuring cost-effectiveness and maintaining product safety during transportation and storage. Cost and time efficiency are major factors driving this trend. Developing simple yet reliable analytical formulas for estimating box strength can significantly reduce the time and resources required for empirical testing [8]. This efficiency is crucial in a fast-paced production environment. Additionally design optimization is facilitated by numerical methods allowing for the simulation of various design scenarios helping manufacturers to optimize box design for specific loading conditions and distribution channels without the need for extensive physical prototyping [9, 19, 23].

Predictive analysis enabled by these methods allows for the prediction of box performance under different environmental conditions such as humidity and temperature fluctuations which are challenging to replicate in physical tests [3]. Furthermore these methods enable customization for specific packaging requirements considering factors like material properties flute size and wall construction which are critical for customizing packaging solutions to individual product needs [18, 19].

This article delves into the critical examination of safety factors essential for ensuring the resilience and reliability of corrugated packaging in the face of such environmental extremes. Understanding and appropriately adjusting these safety factors is not just a matter of maintaining the physical integrity of the packaging but also about safeguarding the quality and condition of the contents within [11]. This becomes particularly crucial in scenarios where the packaging is subjected to prolonged exposure to low temperatures, which can render corrugated materials brittle and less impact-resistant, or high humidity levels, known to weaken the tensile and compressive strength of these materials.

Given the diverse and often unpredictable nature of transportation and storage conditions, this report aims to provide a comprehensive overview of the safety considerations

necessary for corrugated packaging. It underscores the importance of adapting these factors to meet the challenges posed by extreme environmental conditions, thereby ensuring the continued efficacy of corrugated packaging as a key element in the global supply chain.

2. SAFETY FACTORS IN CORRUGATED PACKAGING

Compressive strength in corrugated packaging refers to the maximum load a packaging material can withstand before failing. This measure is crucial in determining how much weight a box can handle before collapsing ensuring that the packaging is suitable for stacking and transport. Burst strength measures the force required to rupture or puncture the wall of corrugated board. This strength is essential to determine how well packaging can hold up to rough handling pressure or stacking forces that might cause it to burst. The Edge Crush Test ECT on the other hand indicates the stacking strength of corrugated boxes. It measures the amount of force a piece of corrugated board can withstand before collapsing on its edge. ECT is key in evaluating the vertical stacking strength of a box critical for designing packaging that needs to support heavy loads or endure high stacking in storage facilities.

Understanding these factors is essential for creating packaging that protects contents effectively during shipping and storage. They are key in determining the overall strength and durability of packaging while balancing factors like cost and material efficiency. Compliance with these metrics ensures consistency and reliability in packaging performance across different applications and industries.

Material quality in corrugated packaging plays a crucial role in determining its strength and durability. Higher quality materials typically exhibit better bonding and consistency leading to improved compressive strength and higher resistance to bursting. The type of paper used the weight and the quality of the fibers whether virgin or recycled all contribute to the overall material quality [16]. Flute size and profile are also key factors in the structural integrity of corrugated packaging. Different flute profiles like A B C E and F offer various degrees of strength and cushioning. Larger flutes provide better stacking strength

suitable for heavier loads while smaller flutes offer better crush resistance and are ideal for packaging requiring high-quality printing. The choice of flute size and profile affects the overall performance of the packaging in terms of strength protection and printability.

Wall construction in corrugated packaging referring to the number of layers of corrugated material like single-faced single-wall double-wall or triple-wall significantly influences its strength and durability. Single-wall construction is common for most standard shipping boxes while double-wall or triple-wall constructions provide enhanced strength and cushioning for heavier or more fragile items. The wall construction determines the packaging's ability to withstand various stresses such as compression impacts and punctures.

These aspects, i.e. material quality, flute size and profile as well as wall construction together determine the key safety factors of corrugated packaging such as compressive strength burst strength and edge crush test ratings. The combination of these elements is essential for designing packaging that meets specific functional and safety requirements ensuring the safe transport and storage of goods.

3. IMPACT OF EXTREME CONDITIONS ON PACKAGING

Low temperatures and high humidity have significant impacts on corrugated packaging which need to be carefully considered for ensuring packaging integrity and performance.

In low temperatures, the fibers in corrugated cardboard become more brittle increasing the risk of cracking or breaking under impact or pressure. Adhesive performance is also impacted as the cold can reduce the effectiveness of adhesives leading to potential delamination and compromised structural integrity. Moving packaging from cold to warmer environments can cause condensation, weakening the cardboard and reducing its load-bearing capacity. Consequently, Edge Crush Test (ECT) and Box Compression Test (BCT) values may decrease as the material becomes less flexible and more prone to fracture under load.

High humidity presents different challenges for corrugated packaging as it weakens the cardboard by softening the fibers.

TABLE 1. SUGGESTED SAFETY FACTOR

Condition/Factor	Suggested Safety Factor Range	Notes/Considerations
Material Quality	1.1 - 1.3	Higher quality materials might need a lower safety factor.
Flute Size and Profile	1.2 - 1.4	Larger flutes provide more cushioning and strength.
Wall Construction	1.1 - 1.5	More layers typically mean higher strength.
Moisture and Humidity	1.3 - 1.6	High humidity weakens corrugated material.
Temperature Extremes	1.2 - 1.5	Extreme temperatures affect material strength.
Duration of Stress	1.2 - 1.6	Long-term storage under load requires a higher factor.
Transportation Vibrations	1.3 - 1.7	Transportation stress can weaken packaging.
Stacking Pattern and Height	1.2 - 1.5	Higher stacks require a higher safety factor.
Product Weight/Distribution	1.1 - 1.4	Heavier/unevenly distributed contents need higher factors.
End-use Environment	1.2 - 1.5	Packaging used in varying environments.
Low Temperature	1.2 - 1.5	Corrugated material can become brittle in cold.
High Humidity	1.5 - 2.0	Humidity can significantly weaken the material.

This results in a significant reduction in compressive and tensile strength. Glue and adhesive degradation is also a concern in humid conditions, potentially leading to structural failures, especially when the packaging is stacked. Moreover, prolonged exposure to high humidity can encourage mold and fungal growth, compromising both the structural integrity and hygiene of the packaging. Like low temperatures, high humidity also adversely affects ECT and BCT values due to the loss of rigidity and strength from moisture absorption.

When corrugated packaging is exposed to both low temperatures and high humidity, albeit not simultaneously, the material undergoes a range of stresses. While low temperatures make it brittle and more prone to cracking, high humidity weakens and softens it. This necessitates careful design considerations, such as using higher-grade materials, incorporating moisture barriers, or adding insulation. To maintain structural integrity under varying conditions, regular testing under simulated environmental conditions is crucial to ensure compliance with relevant standards and maintain the safety and integrity of the packaging.

Understanding and mitigating the effects of low temperatures and high humidity are essential for the safe and effective transportation and storage of goods in corrugated packaging. Table 1 summarizes the safety factors for corrugated packaging

under various conditions, along with their suggested value ranges.

Table 1 provides a general guideline and should be tailored based on specific requirements, testing outcomes, and industry standards.

Discussion of the need for increased safety factors under these conditions.

The need for increased safety factors in corrugated packaging under conditions of low temperature and high humidity is imperative for maintaining the structural integrity and performance of the packaging. Low temperatures can lead to increased brittleness in corrugated materials which means that they become more prone to breaking or cracking under stress or impact. This necessitates a higher safety factor to account for the reduced flexibility and increased fragility of the material. Similarly, the adhesives used in corrugated packaging can lose their effectiveness in cold temperatures leading to potential delamination and structural weakness. In such cases, a higher safety factor would help ensure that the packaging remains intact and functional despite the reduced adhesive strength. High humidity presents a different set of challenges as it weakens the corrugated material by softening the fibers leading to a reduction in both compressive and tensile strength. In environments with high humidity levels, corrugated

TABLE 2. SUGGESTED SAFETY FACTOR ADJUSTMENTS FOR LOW TEMPERATURES

Aspect of Corrugated Packaging	Standard Safety Factor	Adjusted Safety Factor for Low Temperatures	Notes/Considerations
Material Quality	1.1 - 1.3	1.2 - 1.5	Low temperatures can make materials brittle; higher quality materials may be more resistant.
Flute Size and Profile	1.2 - 1.4	1.3 - 1.6	Larger flutes may provide better insulation and structural integrity in cold environments.
Wall Construction	1.1 - 1.5	1.2 - 1.6	Multi-wall construction might offer better performance in low temperatures.
Moisture and Humidity	1.3 - 1.6	1.3 - 1.6	Although humidity is a separate factor, low temperatures can also lead to condensation issues.
Transportation Vibrations	1.3 - 1.7	1.4 - 1.8	Vibrations can have more impact on brittle materials at low temperatures.
Stacking Pattern and Height	1.2 - 1.5	1.3 - 1.6	The brittleness caused by low temperatures can affect stacking strength.
Product Weight/Distribution	1.1 - 1.4	1.2 - 1.5	Uneven weight distribution can be more problematic when material is brittle.

packaging can absorb moisture which significantly diminishes its load-bearing capacity. As a result, there is a need for a greater safety factor to compensate for this loss of strength and rigidity. Furthermore, high humidity can also cause the degradation of adhesives and glues used in corrugated packaging compromising its overall structural stability. Increasing the safety factor in such conditions is crucial to account for the potential weakening of bonding and the overall structure of the packaging.

In addition to these material-specific considerations, the cumulative effect of both low temperatures and high humidity on corrugated packaging necessitates a comprehensive approach to safety factor adjustments. While each condition independently affects the packaging material, their combined impact can be more severe and unpredictable. Therefore, understanding the specific challenges posed by these environmental conditions and adjusting the safety factors accordingly is essential for ensuring the safe transport and storage of goods in corrugated packaging. Regular testing and compliance with industry standards are also key in adapting these safety factors effectively.

4. ADJUSTING SAFETY FACTORS FOR EXTREME CONDITIONS

Table 2 provides suggested safety factor adjustments for corrugated packaging in response to low temperatures.

These values are suggestive and should be tailored based on specific product requirements, material testing, and industry standards. The adjustments are made considering the increased brittleness and potential changes in material properties at low temperatures.

On the other hand, Table 3 illustrates suggested safety factor adjustments for corrugated packaging in high humidity conditions.

The safety factors are adjusted to account for the reduced strength and increased susceptibility to damage in high humidity conditions. These values should be further tailored based on the specific type of corrugated material, the anticipated level of humidity, and the product's sensitivity to moisture. Additional protective measures like moisture barriers or desiccants can also influence these factors.

TABLE 3. SUGGESTED SAFETY FACTOR ADJUSTMENTS FOR HIGH HUMIDITY

Aspect of Corrugated Packaging	Standard Safety Factor	Adjusted Safety Factor for High Humidity	Notes/Considerations
Material Quality	1.1 - 1.3	1.4 - 1.6	High humidity weakens materials; quality is more crucial.
Flute Size and Profile	1.2 - 1.4	1.5 - 1.7	Certain flute profiles may resist humidity better.
Wall Construction	1.1 - 1.5	1.4 - 1.8	Multi-wall construction can provide better resistance.
Moisture Resistance Treatment	1.3 - 1.6	1.5 - 1.8	Treatments for moisture resistance become vital.
Transportation Vibrations	1.3 - 1.7	1.5 - 1.9	Weakened material may respond poorly to vibrations.
Stacking Pattern and Height	1.2 - 1.5	1.5 - 1.8	Humidity can compromise stacking strength.
Product Weight/Distribution	1.1 - 1.4	1.4 - 1.7	Weight distribution is crucial in weaker structures.

5. INDUSTRY STANDARDS AND GUIDELINES

Relevant ASTM [1] and ISO [14, 15] standards play a crucial role in ensuring the quality and safety of corrugated packaging materials among these standards.

- ASTM D642-20 [1] stands out as a critical benchmark for determining the compressive resistance of shipping containers components and unit loads. This standard is essential for assessing how much load a corrugated box can bear before collapsing ensuring that the packaging is suitable for stacking and transport under various conditions.
- ISO 13820:2021 [14] focuses on the description and calibration of fixed platen compression-testing equipment used for testing paper board and corrugated fibreboard. This standard specifies the essential characteristics and principles of calibration for this equipment which is vital for accurate testing of the compressive strength of packaging materials.
- ISO 3037:2022 [15] provides a methodology for determining the edgewise crush resistance of corrugated fibreboard a key indicator of the material's stacking strength. This standard is instrumental in evaluating the vertical stacking capability of corrugated boxes particularly important for understanding how much weight these boxes can support during storage and transportation.
- The FEFCO Technical Specifications [5, 6] offer additional guidance specifically for the corrugated industry focusing on the converting equipment used in producing corrugated materials. These specifications are crucial for those involved

in selecting and operating converting machines ensuring that the finished corrugated products meet the required quality levels.

Additionally the FEFCO Good Manufacturing Practice (GMP) standard updated in 2020 [6] is developed for the manufacturing of packaging made of corrugated board. It supports companies in fulfilling legal requirements according to EU regulations for food contact materials and good manufacturing practices ensuring the safety hygiene and quality of corrugated boxes. Together these ASTM and ISO standards along with FEFCO guidelines provide a comprehensive framework for assessing and ensuring the structural integrity and quality of corrugated packaging materials. Compliance with these standards is essential for manufacturers and suppliers in the packaging industry ensuring that their products are safe reliable and suitable for a wide range of applications.

6. CASE STUDIES AND REAL-WORLD APPLICATIONS

Businesses in various industries have adapted their safety factors for corrugated packaging in response to extreme conditions to ensure the safety and integrity of their products during transport and storage [11]. In the food and beverage industry companies shipping perishable goods have increased safety factors for packaging in high humidity environments. This adjustment accounts for the potential weakening of corrugated boxes due to moisture absorption which is critical in preventing product damage and maintaining hygiene. Standards for burst strength and compressive resistance are

particularly emphasized to withstand the rigors of long-distance shipping and fluctuating humidity levels

In the electronics sector where products are sensitive to temperature fluctuations businesses have adjusted the safety factors of their packaging for low-temperature environments. This includes using higher-grade corrugated materials with enhanced cold resistance and incorporating insulating layers to protect against temperature-induced brittleness and cracking. These measures ensure that electronic goods remain protected from the impacts of cold during shipping especially in winter months.

The pharmaceutical industry also showcases significant adjustments in packaging safety factors for both high humidity and low-temperature conditions. Medicines and medical devices being highly sensitive to environmental conditions require packaging that can maintain its structural integrity under extreme conditions. This has led to the adoption of corrugated boxes with higher safety factors and specialized coatings to resist moisture and temperature changes ensuring that the products remain safe and effective throughout their journey.

Retail and e-commerce businesses dealing with a wide range of products have adopted a flexible approach to packaging safety factors. Tailoring the packaging based on the destination's climate and the product's sensitivity these businesses use variable safety factors to optimize protection and cost-efficiency. This approach involves rigorous testing of packaging materials under simulated environmental conditions and adhering to strict industry standards for material strength and durability.

In summary businesses across different sectors have recognized the importance of adjusting safety factors in corrugated packaging to address the challenges posed by extreme environmental conditions. These adjustments are key to ensuring product safety and quality during transportation and storage while also reflecting a commitment to customer satisfaction and regulatory compliance.

A PRACTICAL EXAMPLE

Let's assume a pharmaceutical company specializing in the transport of temperature-sensitive vaccines faces the challenge of shipping across regions with varying climates including areas

with low temperatures To address this the company adjusts the safety factors for their corrugated packaging to ensure the vaccines remain safe and effective during transportation. Standard safety factors such as compressive strength (BCT) at 1.3; burst strength (BST) at 1.2 and Edge Crush Test (ECT) at 1.5 are re-evaluated for low-temperature conditions

For low temperatures, the compressive strength is increased to 1.5 considering the risk of material brittleness in cold weather. Burst strength is adjusted to 1.4 to ensure the packaging can withstand rough handling which is more likely in cold conditions. ECT is raised to 1.7 to accommodate the increased risk of edge crushing when the material becomes brittle. Additional measures are incorporated into the packaging design including insulating layers to maintain a stable internal temperature and a moisture-resistant coating to protect against potential condensation issues when moving from cold to warmer areas. The company conducts a series of cold chamber tests to simulate the low-temperature conditions validating the adjusted safety factors. This rigorous testing ensures that the new safety factors and additional protective measures are effective. After successful validation, the company adopts these higher safety factors and additional measures for all vaccine shipments to cold regions.

This approach demonstrates a proactive and calculated response to the unique challenges posed by transporting sensitive products like vaccines. The increased safety factors and implementation of additional protective measures are key to maintaining product integrity in the face of environmental challenges ensuring that the vaccines remain safe and effective throughout their journey.

AN ILLUSTRATIVE EXAMPLE.

Let's consider a scenario where corrugated packaging is exposed to both high humidity and significant vibration during transportation. Here's how you might visualize the combined impact on safety factors:

1. **Baseline Safety Factor:** Assume a standard safety factor for corrugated packaging is 1.5 under normal conditions.
2. **Adjustment for High Humidity:** High humidity might require increasing the safety factor by 20%, taking it to 1.8.

TABLE 4. SAFETY FACTORS FOR VARIOUS ENVIRONMENTAL AND STORAGE CONDITIONS

Environmental Factors	Compression Loss	Multipliers
Storage time under load	10 days – 37 percent loss	1.37
	30 days – 40 percent loss	1.40
	90 days – 45 percent loss	1.45
	180 days – 50 percent loss	1.50
Relative humidity, under load (cyclical RH variation further increases compressive loss)	50 % RH – 0 percent loss	1.00
	60 % RH – 10 percent loss	1.10
	70 % RH – 20 percent loss	1.20
	80 % RH – 32 percent loss	1.32
	90 % RH – 52 percent loss	1.52
	100% RH – 85 Percent Loss	1.85

- Adjustment for Vibration:** Transportation vibration might add another 15%, increasing the factor to 2.07.
- Combined Safety Factor:** Instead of simply adding, we consider the compounded effect. The final safety factor might be estimated conservatively as 2.1 or higher, depending on the severity and duration of conditions.

This approach illustrates the need for a cautious and cumulative adjustment of safety factors when multiple stressors are present. The exact values would depend on specific conditions and material testing.

MORE SPECIFIC VALUES

If one is interested in more detailed values of safety factors that depend on storage time, palletization or relative humidity,

comprehensive information can be found in Tables 4 and 5 from Goodwin's work [13].

MEANS OF TRANSPORT

Assigning a specific safety factor for each transportation mode requires careful consideration of the unique stresses and risks associated with that mode. While there are no universally fixed values, one can assume some general guidelines or typical ranges for safety factors for each mode of transportation:

- **Road Transport:** Typical Safety Factor Range: 1.2 to 1.5.
Considerations: Road transport often involves vibrations, impacts from rough roads, abrupt stops, and turns. The safety factor should account for these variables, especially for longer journeys or routes known to have poor road conditions.

TABLE 5. SAFETY FACTORS FOR VARIOUS PALLETIZATION PATTERNS

Pallet Patterns	Loss	Best Case	Worst Case
Columnar, Aligned	Up to 8 percent loss	1.00	1.08
Columnar, misaligned	10-15 percent loss	1.10	1.15
Interlocked	40-60 percent loss	1.40	1.60
Overhang	20-40 percent loss	1.20	1.40
Pallet deck board gap	10-25 percent loss	1.10	1.25
Excessive handling	10-40 percent loss	1.10	1.40

- **Rail Transport:** Typical Safety Factor Range: 1.3 to 1.6. Considerations: Rail transport is characterized by constant vibrations and potential for lateral and longitudinal shocks. The continuous nature of these stresses often necessitates a slightly higher safety factor.
- **Air Transport:** Typical Safety Factor Range: 1.4 to 1.8. Considerations: Air transport involves additional stresses like pressure changes, potential for greater impacts during loading and unloading, and less control over handling. The higher range of safety factor accounts for these increased risks.
- **Sea Transport:** Typical Safety Factor Range: 1.5 to 2.0. Considerations: Sea transport poses challenges like high humidity, saltwater exposure, long-duration vibrations, and heavy impacts during storms. The highest range of safety factor is often used due to these prolonged and varying conditions.

These ranges are general estimates. The specific safety factor for the packaging should be determined based on more detailed analysis of the product, packaging material, and specific transportation conditions. It's advisable to conduct rigorous testing, including simulated transportation conditions, and consult industry standards (like ISO or ASTM) for more precise safety factor determination. The fragility and value of the product being shipped can also influence the required safety factor. More delicate or valuable items may necessitate higher safety factors. The overall environmental conditions (e.g., extreme temperatures) and handling practices (e.g., manual vs. automated) during transportation should also be factored into the safety factor calculation. Ensure that your packaging meets any specific regulatory requirements for the regions and countries you are shipping to or through.

These safety factors are an additional margin of security over and above the expected maximum stresses to ensure that the packaging can withstand unexpected situations without failing.

7. CONCLUSION

The study of safety factors in corrugated packaging under extreme environmental conditions reveals key insights essential

for the packaging industry. Corrugated packaging must be designed to withstand challenges such as low temperatures and high humidity which can significantly impact material properties leading to reduced strength and integrity. Adjusting safety factors for compressive strength burst strength and edge crush test is crucial in these conditions. Material quality, flute size and wall construction play vital roles in determining these safety factors ensuring the packaging is robust enough to protect contents under varying environmental stresses.

The findings highlight the need for businesses to adopt a proactive approach in adjusting safety factors based on specific environmental challenges faced during transportation and storage. Rigorous testing and adherence to industry standards like ASTM and ISO are recommended to ensure packaging reliability and safety. This approach not only ensures the protection of goods but also enhances the efficiency and reliability of supply chain operations.

Recommendations for industry practices include regular material testing under simulated environmental conditions, careful selection of packaging materials based on product, transportation needs and continuous monitoring or reassessment of packaging performance in different environments. Companies should also stay updated with the latest developments in packaging technology and materials to continually improve their packaging solutions. In summary understanding and effectively responding to environmental challenges in packaging is key to maintaining product safety and quality while also meeting consumer and regulatory expectations.

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