

Use of Frozen Silt Mat, an Alternative to Crane Timber Mat to Minimize Energy as Ninth Waste and to Reduce CO₂ Emissions

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Abstract - The fourth revolution in industry is all about process automation, optimization, and intelligence. Energy optimization is one of the critical aspects of Industry 4.0. Energy as the ninth waste in lean manufacturing results in CO₂ emissions as a by-product. The practitioners take diverse initiatives to mitigate the impact of CO₂ emissions by encouraging energy usage reduction. The impact of CO₂ emissions on the environment is a significant concern for the 21st century. Organizations around the world are adopting novel sustainable approaches to minimize energy utilization to lessen the environmental impact. In the same way, modular construction uses lean concepts to minimize the seven wastes and, directly or indirectly, reduces energy utilization. With the advent of modular construction, the application of high-capacity mobile cranes surged. For modular construction activities, the crane industry uses crane mats, usually timber mats, for soil stability underneath the high-capacity mobile cranes. This research encompasses the calculations for the indirect/direct CO₂ emissions of timber mat utilization versus a novel application of crane mats prepared of frozen silt. The finite element simulation estimates the equalling of frozen silt against Coastal Douglas-Fir mats, dependable upon construction site ambient temperature constraint. The results show a promising impact of using frozen silt in energy wastage and CO₂ emissions reduction.

Keywords: Modular Construction, Energy Wastage, CO₂ Emissions, Crane Mats, Frozen Silt, Finite Element Analysis

1. Introduction

Created in the Japanese car industry, Lean Manufacturing currently remains a leading approach worldwide for industries. It intends to diminish waste and improve value (high quality, low cost, short lead times) [1]. Lean manufacturing experts identified seven types of waste in product development: overproduction, defects, inventory, over-processing, transportation, waiting, and motion. The three instances of Industry 4.0 meeting Lean are continuous improvement, putting customers first, and eradicating waste in the value chain [2]. Therefore, the main objective of lean is customer satisfaction, quality, and responsiveness. However, there has been a growth in customers wanting environmentally sustainable products. Organizations are compelled by customer satisfaction and environmental regulations to re-examine these objectives [3].

Environmental pollution is one of the significant concerns brought forward by the sustainability movement. The crippling impact has put industries on caution to imminent fate if a better move is not made in time [4], [5]. Environmental effects can be considered because of 'green wastes.' Like lean, eight wastes are categorized under green waste: Greenhouse Gases (GHG), Eutrophication, Excessive Resource Usage, Excessive Water Usage, Excessive Power Usage, Pollution, Rubbish and Poor Health & Safety [6]. In 2015, Canada's total GHG emissions were 722 mega tonnes (Mt) of carbon dioxide equivalent (CO₂ emissions), as shown in Figure 1 [7], [8]. Residential, commercial, and industrial buildings are responsible for 17% of Canada's GHG emissions [9]. The International Energy Agency (IEA) has highlighted the need for energy efficiency measures to reduce by two-thirds in the energy intensity of the global economy by 2050 [10]. Figure 2, Canada contributes to 2% of the emissions but has the highest emissions per capita [11].

Many countries are imposing carbon tax as a step towards lowering GHG emissions. Similarly, Ottawa (Canada) declared that each province would require a cost on carbon discharges of \$20 per ton of emission by January 1, 2019. This cost will increase by \$10 every year until it reaches \$50/ton in 2022 [12]. Apart from government initiatives, the construction industry has evolved to increase productivity and lower its carbon footprint. The construction industry utilizes approximately 50% of the natural resources and uses 70% of wood materials, which results in high levels of CO₂ emissions [13]. The

proposed research methodology substitutes conventional crane matting solutions with frozen silt mat and analyzes its impact on energy utilization and CO₂ emissions. The environmental effects of frozen silt mat technology are investigated in this contribution to compare the CO₂ emissions between timber mats and frozen silt.

As per the research done by Ali (2018), the work on construction sites in Northwest Canada usually continues for eight months, therefore using frozen silt mat for the shoulder season results in cost savings and energy saving in the form of lower CO₂ emissions. The shoulder season is assumed to be approximately one month when the ambient temperature is close to -10°C. The mechanical properties of frozen silt mat at -10°C are at par with Coastal Douglas-Fir [14]. A bottom-up estimate for CO₂ emissions sums up to analyze energy wastage, each workday for one month. The results show the promising impact of using frozen silt to reduce CO₂ emissions. These calculations can build a foundation for the practical use of frozen silt as a crane mat for modular construction in the cold regions of North America.

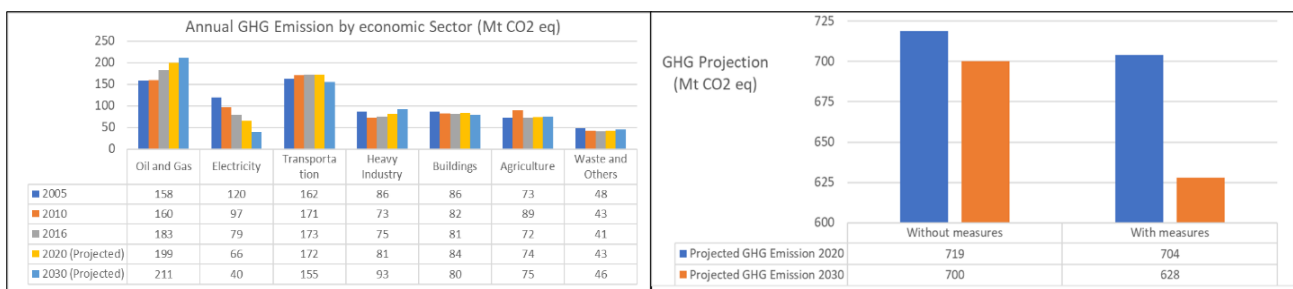


Fig. 1: Canada's Greenhouse Gas Emitting sectors and Estimated Future GHG Emissions. Source: Adapted from Government of Canada, "Canada's greenhouse gas and air pollutant emissions projections.," Gatineau, QC, 2018.

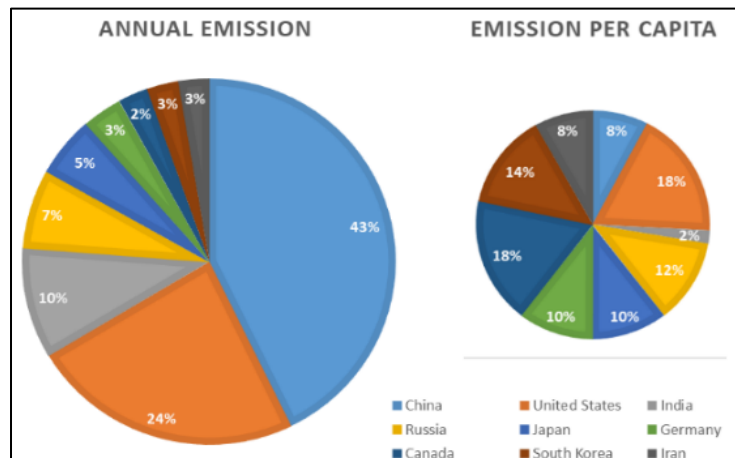


Fig. 2: Annual CO₂ Emissions of Nine Major Countries VS per Capita. Source: Adapted from Union of Concerned Scientists, "Each Country's Share of CO₂ emissions," 2020. [Online]. Available: <https://www.ucsusa.org/resources/each-country-s-share-co2-emissions>.

2. Literature Review

2.1. Current Construction Methodologies

There are two main types of construction methodologies: on-site and off-site construction, also known as modular construction. On-site construction involves transporting all disassembled material such as wood/timber, steel, concrete and then framing and structuring those materials at the construction site. Off-site modular construction requires planning, designing, fabricating, and assembling building elements at a separate location away from the actual construction site. The modular method uses lean principles to convert internal processes to external ones and decrease project completion

time, reducing CO₂ emissions. Overall, modular construction decreases the carbon footprint of the construction industry [15]. Al-Hussein, Manrique, & Mah [15] research indicates that 43% of CO₂ emissions can be reduced by adopting modular construction. A relative comparison was conducted by Al-Hussein, Manrique, & Mah [15] using the construction of a residential building where both methodologies were employed and analyzed. This study showed that on-site construction produces 431 Metric tons of CO₂ emissions, whereas modular construction (off-site construction) produces only 247.23 Metric tons of CO₂ emissions (see Figure 3), with a 42% reduction. The adoption of modular construction also decreased project completion time from 10.8 months to 6.5 months [15].

Seo, Kim, Hong, & Kim [16] evaluated the impact of the material production, material transportation, and construction phases from a construction site perspective. In addition, CO₂ emissions were examined by Seo, Kim, Hong, & Kim [16] through the system capacity and gross floor area for each work type. Calculations showed that CO₂ emissions from the material production phase constitute 93.4% of CO₂ emissions [16]. CO₂ emissions from material transportation and on-site construction account for 2.4% and 4.2% of the total CO₂ emissions, respectively. The research concluded that selecting appropriate input materials and resources was vital to reducing CO₂ emissions [16]. The life cycle of buildings is usually divided into the production of materials, transportation of materials, construction phase, operational and maintenance phase, and dismantling and disposal phase. All these phases contribute to different levels of CO₂ emissions. While there are six types of main factors contributing to global warming (CO₂, CH₄, N₂O, HFCS, PFCS, and SF₆), as defined in the United Nations Framework Convention on Climate Change, the subject of this study is the calculation of CO₂ emissions [23]. The research showed that concrete works account for a high level of CO₂ emissions in the material production phase (see Figure 3), of 1,011.3 Tons of CO₂ emissions [16]. In the material transportation phase, the CO₂ emissions equal 107.7 Tons of CO₂ emissions, which makes up 2.4% of the total CO₂ emissions [16].

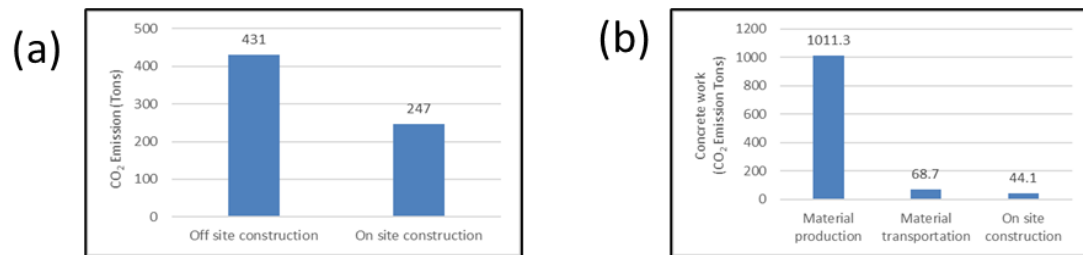


Fig. 3(a): Difference in Energy Released During On-Site and Off-Site Construction: Adapted from M. Al-Hussein, J. D. Manrique and D. Mah, "North Ridge CO₂ Analysis Report Comparison between Modular and On-Site Construction," Edmonton, 2009. [15], (b): Construction Process Energy Waste: Adapted from M.-S. Seo, T. Kim, G. Hong and H. Kim, "On-Site Measurements of CO₂ emissions during the Construction Phase of a Building Complex," *Energies*, vol. 9, no. 599, pp. 1-13, 2016 [16].

2.2. Construction Equipment

One of the most common types of equipment used on construction sites is a mobile crane. The ground pressure developed by a crane can be very high, and its track/outrigger generates significant pressure on the ground surface. Many soils and locations on a job site cannot withstand high equipment pressure without soil failure, which can cause a crane to topple over. Currently, the two most common crane mats used in Canada are Coastal Douglas-Fir timber mats and steel mats [17]. Excessive energy is used to produce and transport these mats to construction sites [18]. The research methodology outlined in this contribution will discuss how to reduce CO₂ emissions released in the production and transportation of timber mats with a more energy-saving solution such as frozen silts, a substitute conventional crane matting solution, and analyze its impact on CO₂ emissions using a hypothetical case study. The environmental impact of frozen silt mat technology will be analyzed to compare the CO₂ emissions between timber mats and frozen silt mats under extreme weather conditions.

2.3. Frozen Silt as Crane Mat Material

The construction industry relies upon using cranes to build the structures needed. With the advent of off-site construction as the cost-effective solution for the construction industry automation, complete projects are delivered to the construction site in the form of modules, which have become heavier over the years due to the increasing number of parts combined and

joined together. As a result, high-capacity cranes became the backbone for the assembly/installation of modularized plants/structures. Since the weight of the lifting system (crane and payload) has become heavier, ignoring the allowable bearing capacity under the crawler crane tracks/outriggers by the practitioners can lead to the ground's failure, resulting loss of life and property. The traditional norms to raise the soil bearing capacity proceeds in two phases: ground a layer (or a mix of layers) of construction aggregates compacted, and/or addition of timber mats (1, 2, or 3 layers of mats). With the adoption of the modular construction paradigm, the demand for crane mats augmented. As a result, the cost drivers associated with the stacking and transportation of timber mats to and from the construction site also surged. However, the production of these mats remained the same or increased a little. According to a market research report published in 2014, the mat demand in Canada annually is around 450,000 to 750,000 [17]. The production of these mats in Canada is only about 20,000 to 25,000 per year. Even the production in North America is not more than 600,000 per year. (see Figure 4). The growth of the mat industry is about 200% from 2009 to 2014 [17].

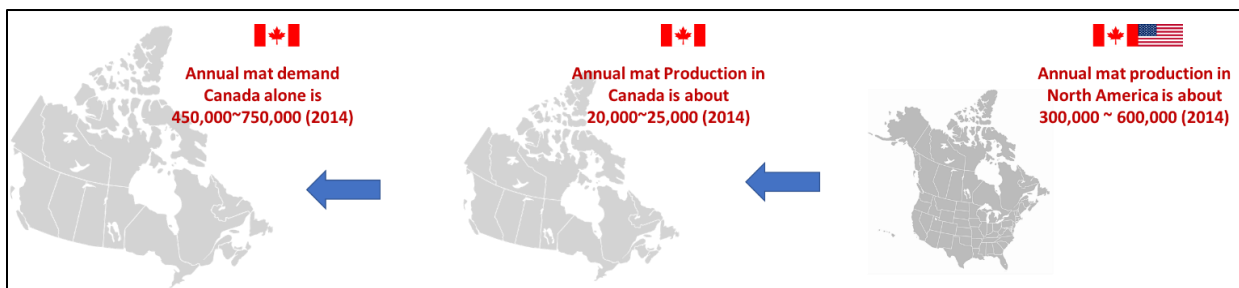


Fig. 4: Mat demand and supply gap for Canada. Adapted from Golden Environmental Mat Services, “2014 ACCESS MAT RESEARCH: PERSPECTIVES ABOUT THE INDUSTRY AND ASSET TRACKING CONCEPT,” Calgary, 2015.

Ali [18] conducted research to show that frozen silt has properties similar to the supporting structural material wood [14], [18]. Considering the mechanical properties of frozen silt (a frozen mixture of water and silt), the uniqueness of using it as crane matting is a novel idea that transcends traditional constraints and helps minimize environmental impact. The mechanical properties of frozen silt are comparable to timber matting (Coastal Douglas-fir) but are dependent upon the temperature constraint (i.e., the mechanical properties of frozen silt with the temperature at/below -10°C are comparable to Coastal Douglas-Fir) [3]. For the finite element analysis, the study used a standard size mat. The competitive analysis was established by Ali [18] on the traditional selection criteria of the crane mat, which is the compressive stress transferred to the ground. The required mat surface temperature for frozen silt was -10°C for the analysis, based on its practical usage and finite element simulation (see Table 1).

Table 1: Linear mechanical properties for comparison

		Units	Coastal Douglas-Fir	Frozen silt
1	Young's Modulus	MPa	13,400 [19]	10,000 [20], [21]
2	Poisson's Ratio		0.449[22]	0.3[3]
3	Tensile Yield Strength	MPa	2.3[19]	5.1[21]
4	Compressive Yield Strength	MPa	5.0[19]	5.0[21]
5	Tensile Ultimate Strength	MPa	5.0[19]	5.1[21]

The authors of this contribution performed the finite element simulation under similar boundary conditions as of work conducted by Ali [18]. The outcome in stress maps provided a promising approach for using frozen silt as an alternative to Coastal Douglas-Fir. The results show that the crane mats made of frozen silt and Coastal Douglas-Fir are similar in behavior within the constraint of compressive stress distribution (see Figure 5). The compressive stress under the crawler crane track front (left and right) for Coastal Douglas Fir is close to frozen silt, under similar boundary

conditions, while the superstructure slew from left front to left side. That is why the stress value increases for the left front as the superstructure slew from the left front (0°) to the left side (90°). The stress value is maximum when the crane boom is directly over the crawler track. This phenomenon is due to the change of ground bearing pressure under the crawler track due to superstructure slew [23]. The findings build a strong foundation for using frozen silt mats to alternative timber mats (Coastal Douglas-Fir). Based on the outcome, the bottom-up estimation of capital and operating costs of frozen silt mat can be generated [18].

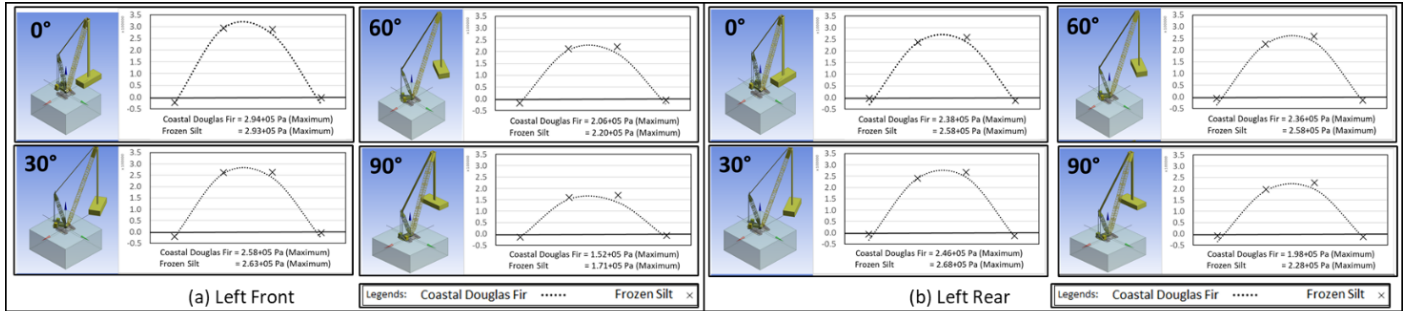


Fig. 5: Compressive Stress values under crawler tracks (a): Left Front, (b): Left Rear.

3. CO₂ Emissions Calculations

One of the indicators to measure CO₂ emissions is to measure the wastage of energy resources. In terms of frozen silt mats, the environmental impact is to reduce CO₂ emissions. The target is to introduce new methods to minimize the construction industry wastes, to make it more efficient and productive. The authors of this contribution initiate the comparison between timber mat usage and frozen silt mat usage. For comparison, a hypothetical project is assumed at Yellowknife (Northwest Territories, north of Alberta, Canada). The main ingredient of frozen silt is silt (soil), and ambient temperature of -10°C. Figure 6 shows, about 7.5 months in one year, the average temperature is below freezing [24]. Based on these values, the assumption is that the hypothetical project is located close to Yellowknife. The project's duration (assumed) is one month, i.e., within shoulder season (October, November, April, and May) because the average temperature is below -10°C. These months lie on the shoulder season, which means work continues as the temperature is bearable for the workers on site. The total number of days below -10°C is about 44.5 (see Figure 6), available during the shoulder seasons of October, November, April, and May. For the hypothetical project, the crane assumption is Manitowoc 18000, a crawler crane, which requires eight timber mats (3.6449 m × 2.4384 m × 0.2032 m), 4 for each crane track, and in the case of frozen silt mats, it requires two frozen silt mats (14.58 m × 2.4384 m × 0.2032 m) (see Figure 7). The lifespan of timber mats is three years (maximum) [14]. The total volume of 8 timber mats is 14.448 m³. The density of Coastal Douglas-Fir is about 0.52997 Metric Ton/m³ [25]. Based on this density, the weight of these mats is 7.657 Metric Tons. The first thing is to calculate the CO₂ emissions during timber manufacturing. Equation (1) proposed by Bergman et al. [13] can be used to calculate the CO₂ emissions in metric tons, which is equal to 0.7272 of wood weight in metric tons.

$$CO_2 (\text{Manufacturing}) = 0.7272 \times W_g \quad (1)$$

One of the significant indirect CO₂ emissions (Metric Tons) is transportation from the forest to the manufacturing plant and the manufacturing plant to the crane yard as the final product. Equation (2), proposed by Whittaker et al. [26], can be used by the practitioners for the calculations.

$$CO_2 (\text{transport}) = 0.032 \times W_g \times (D_m + D_y) \quad (2)$$

Where W_g = weight of the wood (Metric Tons), D_m = distance traveled from forest to manufacturing, and D_y = distance from manufacturing to the crane yard. As Coastal Douglas-Fir is readily available in Canada in the form of raw material, the

average distance for the raw/finished product travel is about 500 Km ($D_m + D_y$) (assumption). Based on these values, the total CO₂ emissions are about 0.1225 Metric Ton.

The assumption is that the practitioners use the frozen silt mat for crane lifting on the construction site for one (30 days in total) in one year. The requirement is to calculate the CO₂ emissions for one month of timber mat usage. The span of timber mat is three years maximum. If only timber mats are used on the construction site, they last for eight per year [14]. Based on these constraints, the practitioners can calculate the CO₂ emissions (Metric Tons) for one month (30 days in total) using the equation (3). The approach is to compare one-month utilization of timber mats and frozen silt mats to calculate CO₂ emissions.

$$Indirect\ CO_2 = \left(\frac{CO_2 (Manufacturing) + CO_2 (transport)}{8 \times 3} \right) \times n \quad (3)$$

Where n = number of months for timber mat usage, in the case of frozen silt mats usage, $n = 1$. The indirect CO₂ emissions are about 0.237 Metric Ton. For direct CO₂ emissions, the authors of this contribution assumed the crane yard in Edmonton, Alberta, Canada, and the distance between Edmonton (Alberta, Canada) and Yellowknife (Northwest Territories, Canada) is about 1,452 Km. The total traveling distance for timber mats is about 2,904 Km. Equation (2), in a modified form as equation (3), can be used for the calculation of direct CO₂ emissions (Metric Tons) [26].

$$CO_2 (transport) = 0.032 \times W_g \times D_l \quad (4)$$

Where D_l = total distance traveled from yard to site and from site to the yard, the direct CO₂ emissions is about 0.122 Metric Ton for 1,452 Km and 7.657 Metric Tons (wood weight). The total CO₂ emissions for timber mats for one project and one month is about 0.949 Metric Ton (indirect + direct CO₂ emissions). In the case of frozen silt mat, the essential ingredient is soil/silt and -10°C. These ingredients are readily available on-site during shoulder season and free of cost. The CO₂ emissions for frozen silt will be negligible, i.e., zero for the frozen silt mats (see Table 2).

Table 2: CO₂ emissions Calculations

		Timber Mats	Frozen Silt Mats
1	Indirect CO ₂ emissions	0.237 Metric Tons	0
2	Direct CO ₂ emissions	0.712 Metric Tons	0
3	Labor and Equipment on Site CO ₂ emissions	Assumed same for both	
4	Total CO ₂ emissions	0.949 Metric Ton	0

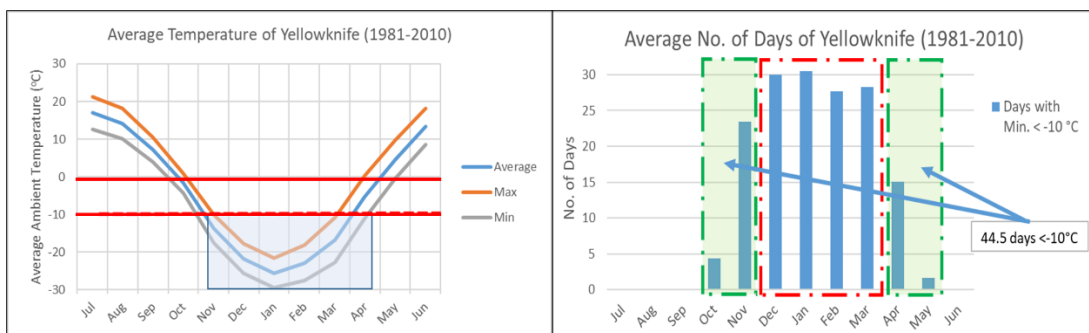


Fig. 6 (a): Average temperature of Yellowknife (b): No of days with ambient temperature below -10°C at Yellowknife. Data from Government of Canada, “Canadian Climate Normals,” 2021. [Online]. Available: https://climate.weather.gc.ca/climate_normals/.

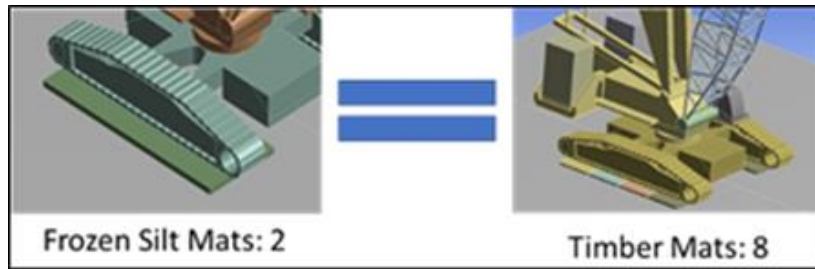


Fig. 7: Timber mats requirement VS Frozen Silt Mats.

4. Conclusion

The calculations state that about 0.949 Metric Ton of CO₂ emissions can be saved by using the novel approach of frozen silt mat in cold regions of North America instead of using Timber mats. For the calculations for energy wastage, one Metric Ton of CO₂ emissions is equal to 1,414.43 KWh or 112.53 gallons of gasoline [27]. Using a similar conversion, the 0.949 Metric Ton (see Table 2) of CO₂ emissions means 1,342.30 KWh of energy is saved using frozen silt mats, or 106.79 gallons of gasoline. The research conducted in this contribution concludes that using frozen silt mat can reduce energy wastage.

5. Future Aspects and Recommendations

This contribution is restricted to the climate of Yellowknife (Northwest Territories, Canada), more precisely, the weather of North America. The behavior of this novel approach under different climate conditions needs investigation using finite element analysis and actual lab/site testing. For this research, the site activities are considered negligible, but for future research aspects, this needs to be investigated in detail to incorporate the energy cost drivers in detail. In addition to the current research, different project scenarios need to be explored in the future to define the actual requirement. Additional research is required to investigate the usage of frozen silt mats compared to steel mats or plastic mats on construction sites, in direct and indirect CO₂ emissions, which leads to energy wastage, as ninth waste.

6. References

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