Physical and Numerical Modelling of   
Rockwool Insulated Landfill Liner Materials   
as a Heat Mitigation Method

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| **ABSTRACT** The growing global amount of waste emphasizes the urgency of effective landfill management. The large amount of organic matter in landfill liners undergoes rapid biodegradation, generating significant heat. This heat production can cause various environmental issues, such as the release of volatile organic compounds, an increased risk of groundwater contamination from leachate migration, unpleasant odors, and a reduction in the structural integrity of the landfill liner. Therefore, efficient heat mitigation methods in landfill liners are crucial for minimizing detrimental environmental effects. Utilizing insulation material in landfills can be an effective and novel method in the environmental geotechnical field while promoting material sustainability. This study aims to evaluate the effectiveness of rockwool as an insulation material in reducing heat transfer inside landfill liners. The effectiveness of rockwool was assessed by using both physical and numerical modelling with varying thicknesses of rockwool, moisture conditions, and elevated temperatures in the landfill liner system. The insulated landfill liner system was simulated numerically using ANSYS software. A wooden box prototype was built to simulate a real-life insulated landfill liner system to evaluate the feasibility of insulation material as a heat mitigation method in landfills. The findings suggest that rockwool is effective in mitigating the heat in landfill liners. Overall, rockwool reduced the elevated temperatures up to 48.45% despite the system being wet which reduces the effectiveness of insulation performance. Comparatively, the 20 mm rockwool was efficient in minimizing average level of elevated temperatures, meanwhile, rockwool with thicknesses of 35 mm and 50 mm were needed to attenuate extremely elevated temperatures. These results were demonstrated through numerical simulation and validated by physical modelling results. It can imply an effective method for mitigating heat in landfill liners, which advances the development of environmental geotechnics for sustainable waste management.  **KEYWORDS** Environmental geotechnics, heat mitigation, insulation materials, landfill liner, waste management |

# INTRODUCTION

Municipal solid waste (MSW) landfills are waste management facilities that produce a significant quantity of heat. The heat in landfills is a byproduct of the decomposition of organic matter in MSW by bacteria as well as by chemical and biological reactions that take place inside the waste. Along with heat, gas and leachate are the main byproducts of the decomposition of the organic MSW (Hanson et al., 2013). The heat produced in a landfill can lead to elevated temperatures (ETs). ETs can be defined as temperatures exceeding the ambient air temperature as a result of heat generation in the landfill (Jayawardane et al., 2021). Temperatures exceeding 35 °C in landfills can negatively affect the performance of the liner (Yoshida and Rowe, 2003). ETs phenomena are crucial to be mitigated since they can cause serious environmental risks in landfills, such as increased greenhouse gas emissions, leachate generation, instability in the soil structure, and in extreme cases may lead to fire outbreaks. Thus, creating efficient heat mitigation plans is essential part of sustainable and responsible management of landfills.

Various mitigation strategies have been studied to reduce the negative effect ETs. Some heat mitigation methods, such as gas collection systems, cover systems, and leachate management systems, are even required as part of local regulations and integrated with the landfill system (Cortellazzo et al., 2022, El-Saadony et al., 2023). Other innovations that have been studied include heat extraction by using the waste-to-energy concept and heat regulation by using the heat exchanger concept (Yesiller et al., 2016). However, these methods have limitations: gas collection systems have limited impact on heat reduction and primarily target gas emissions; cover systems trap heat and degrade materials over time; while leachate management systems mainly tackle leachate issues and require significant energy. Innovations like waste-to-energy and heat exchanger systems also bring new challenges such as high maintenance costs and complexity (Gewald et al., 2012).

Utilizing thermal insulation materials in MSW landfill liners is an innovative and novel strategy that was initially proposed by Hoor (2011), showcased by using numerical modelling method. The idea of insulating materials is to minimize the amount of heat transfer between the waste inside the system and the environment outside. This method provides a passive system to reduce heat in the landfill liners without the operational demands of active systems. This method entails incorporating insulation materials inside the structure or on its exterior, for example, foam boards, mineral wool, clay, polymer, and synthetic geomembranes. The thickness of the materials used may also affect the insulation performance.

A material that is well-known for its effective thermal properties as an insulator is mineral wool such as rockwool. Rockwool has low thermal conductivity and a porous structure to reduce the heat transfer from the system to the surrounding environment (Djurovic-Petrovic, 2015). Compared to other insulation materials, rockwool is more affordable and widely available. It also has suitable shape and practical to work with for large-scale landfill applications. Moreover, rockwool can also be a new solution to sustainability problems and an important element of the circular economy due to its recyclability and long-lasting characteristics. However, previous works have studied the application of rockwool as an insulation material limited to building usage only. It is important to incorporate the study of rockwool in the context of landfill liner utilization. Apart from effective thermal properties, landfill liner materials also need to possess long-term integrity and low environmental impact (Hoor and Rowe, 2012). A model of landfill liner insulated with rockwool with various thicknesses needs to be carried out as the solution to the mentioned problem.

Landfill liner prototypes have been modelled by numerical simulations in several studies. A heat generation model in landfills correlated to gas production rate was developed by Yoshida and Rowe (2003). Another numerical study was conducted by Hoor and Rowe (2012) on the design and operation of parts in landfill systems while being exposed to ETs have also been done. Analysis of insulated landfill liners using the encapsulated fiberglass and extruded polystyrene were studied by Benson et al (1996). In this paper, numerical simulation that further explores heat transfer characteristics in a rockwool-insulated landfill liner system is carried out. The effectiveness of rockwool with different thicknesses as the insulation material in landfill liners are modelled. The numerical simulation was carried out using ANSYS. In addition to the numerical simulation, a physical model scale experiment of rockwool-insulated landfill liner was also carried out. The physical prototype validates the numerical results and ensure the feasibility of rockwool usage in landfill system. This study contributes to the development of more environmentally friendly landfill systems, providing insights of insulated landfill liner under several conditions, and contributing to utilization of sustainable material.

# MATERIALS AND METHODOLOGY

## Materials

### Marine Clay

Marine clay was used as a compacted clay liner (CCL) for the landfill liner system physical modelling. The marine clay was collected from a coastal region located in Kampung Dungun, 45800 Jeram, Selangor, Malaysia. Marine clay in different states is presented in Figure 1(a) and (b) and its properties are shown in Table 1.

|  |  |  |
| --- | --- | --- |
| A pile of small rocks  Description automatically generated  **(a)** | A bowl of white powder  Description automatically generated  **(b)** | A brown square object on a white surface  Description automatically generated  **(c)** |

Figure 1. (a) Marine clay uncrushed and dried; (b) crushed and dried condition; (c) and rockwool in the form of insulation board.

Table 1. Properties of marine clay (Jayawardane et al., 2021)

|  |  |  |
| --- | --- | --- |
| Properties | Value | Units |
| Natural water content | 60.46 | % |
| Specific gravity | 2.48 |  |
| Maximum dry density | 1.54 | g cm-3 |
| Optimum moisture content | 24.2 | % |
| Linear shrinkage | 14.2 | % |
| Thermal conductivity | 0.797 | W m-1 K-1 |
| Volumetric heat capacity | 1.893 | MJ m-3 °C-1 |
| Thermal diffusivity | 0.613 | mm2 s-1 |
| Thermal resistivity | 125 | °C cm W-1 |
| Unconfined compressive strength (UCS) | 168 | kPa |

### Rockwool

The rockwool used was obtained from ROCKWOOL Asia company in Kelaniya, Sri Lanka. The rockwool insulation board’s thicknesses utilized are 20 mm, 35 mm, and 50 mm. Previous research showed that thicknesses over 50 mm for building insulation led to a decline or insignificant rise in net energy savings (Yildiz et al., 2008). The rockwool used for this study is presented inFigure 1(c). Typical properties of rockwool are presented in Table 2.

Table 2. Typical properties of rockwool (Lu et al., 2019)

|  |  |  |
| --- | --- | --- |
| Properties | Value | Units |
| Density | 40-200 | kg m-3 |
| Compressive Strength | 40-300 | kPa |
| Moisture Resistance | Not waterproof but can be dried easily | - |
| Chemical Resistance | Quite not resistant especially to water-based chemical | - |
| Thermal conductivity | 0.034-0.045 | W m-1 K-1 |
|  |  |  |
| Volumetric heat capacity | 0.100-0.200 | MJ m-3 °C-1 |
| Thermal diffusivity | 0.1-0.3 | mm2 s-1 |

### Additional materials and equipment

Additional materials and equipment used for physical modelling in this paper are sand, a wooden box, thermocouple probes, resistance temperature detection (RTD) probe, portable data logger, and heat pad. The specifications and functions of each material/equipment are shown in Table 3.

Table 3. Additional materials and equipment used for the landfill prototype

|  |  |  |
| --- | --- | --- |
| Materials/Equipment | Dimensions/Specification | Function |
| Sand | Made into a layer with a thickness of 25 mm | As the temperature detection sand layer (TDSL) |
| Wooden box | 300 mm x 300 mm with a wall thickness of 20 mm | As a container for landfill prototype to prevent heat exposure between the system and environment |
| Thermocouple probes | Ultra-thin with a diameter of 1.5 mm | Detect temperature variation within the CCL throughout the experiment |
| Resistance Temperature Detection (RTD) probe | Probe with a diameter of 6 mm and length of 150 mm that was Connected to the Proportional Integral Derivative (PID) controller | Detect and maintain temperature within the TDSL |
| Portable data logger | TDS 150 type by Tokyo Sokki Kenkyujo Co., Ltd | Connected with probes to quantify temperature |
| Heat pad | Electric pad that was connected to a 40 Ampere solid state relay (SSR) and a GT8 ATS 210 proportional integral derivative (PID) controller | As the heat source for the landfill's physical prototype |

## Methodology

### Thermal conductivity test

The thermal conductivity of the marine clay, rockwool, and sand was measured by using the TEMPOS Analyzer. This test was conducted by following the ASTM D5334 standard, which determines the thermal properties of materials by thermal needle probe. The thermal conductivity of each material was tested under dry and wet conditions to replicate real-case scenarios of a landfill site. Materials under wet conditions are prepared by immersing in water at room temperature for 24 hours, reaching an equilibrium state in accordance with ASTM D570, the standard for water absorption testing. Additionally, moisture content has a direct influence on the thermal conductivity of a material (Modi et al., 2014). The results of this test are shown in Section 3.1, Table 5.

### Numerical modelling

ANSYS was chosen as the software to simulate the insulated landfill liner system that is exposed to constant elevated temperatures (CET) and moisture content. The moisture content in the study referred specifically to the liquid water through the layers in landfill system. The output of numerical modelling was the temperature profile in the landfill liner system with the visualization of temperature distribution. Sixteen different variations of the numerical modelling system are shown in Table 4.

The analysis system used in numerical modelling was the steady-state thermal system. This approach was chosen to simplify the analysis and focus on the thermal behavior and conditions that most significantly influence the performance of landfill liners. Steady-state numerical modelling was also effective in replicating larger real-life scenarios on a smaller scale prototype (Wang et al., 2024). The obtained material properties were used as input engineering properties of ANSYS. The experimental setup was created as a 2D geometric model and extruded into a 3D model by using ANSYS DesignModeler with the size of 300 mm x 300 mm x 155-185 mm (depending on rockwool’s thickness) The model developed in this study was smaller in scale to emphasize the critical thermal interactions within the insulation and CCL layer and it can be extrapolated to larger size in further studies for full-scale applications.

Table 4. Configuration of insulation materials that were used in numerical modelling

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Configurations | Moisture conditions | CET (oC) | Insulation Material | Thickness |
| 1 | Dry | 40 | No insulation | - |
| 2 | Rockwool | 20 mm |
| 3 | Rockwool | 35 mm |
| 4 | Rockwool | 50 mm |
| 5 | 70 | No insulation | - |
| 6 | Rockwool | 20 mm |
| 7 | Rockwool | 35 mm |
| 8 | Rockwool | 50 mm |
| 9 | Wet | 40 | No insulation | - |
| 10 | Rockwool | 20 mm |
| 11 | Rockwool | 35 mm |
| 12 | Rockwool | 50 mm |
| 13 | 70 | No insulation | - |
| 14 | Rockwool | 20 mm |
| 15 | Rockwool | 35 mm |
| 16 | Rockwool | 50 mm |

The model consists of sand as TDSL, rockwool insulation layer and marine clay as CCL. The 110 mm CCL was separated into six layers with different thicknesses, corresponding where the thermocouples were installed in the physical model. The first three layers were thinner to capture the larger temperature gradient at the uppermost region of the CCL while being exposed to CET. A schematic sketch of TDSL, insulation layer, and CCLs in ANSYS DesignModeler is shown in Figure 2(a). All bodies were grouped into a single model and transferred to be meshed in ANSYS Meshing. The mesh was generated using the "Mechanical" physics preference, default element size, and growth rate of 1.2 as per recommendation from ANSYS. The isometric sketch of meshed geometric model that comprised a total of 12,096 nodes and 1,575 elements is depicted in Figure 2(b).

|  |  |
| --- | --- |
| A graph with different colored stripes  Description automatically generated with medium confidence  **(a)** | **(b)** |

Figure 2. (a) 2D schematic sketch of landfill system modelling in ANSYS DesignModeler; (b) Isometric sketch of meshed landfill system modelling in ANSYS.

The boundary conditions of the simulations including initial temperature, CET, and heat source were initially defined. Initial temperatures were set to room temperature of 25 oC, meanwhile, CET was analyzed at 40 oC and 70 oC. The temperatures used 40 °C and 70 °C were the average and extreme ETs for basal liners in MSW landfills during waste generation, respectively (Bouazza et al., 2011). The heat flow was not calculated by using temperature boundary conditions since they do not adequately represent dynamic thermal processes in the landfill. The heat flow from waste was conduction type with the value calculated by using Equation (1) to represent heat generation rate for observing thermal behavior in landfill system (Yesiller et al., 2016).

|  |  |
| --- | --- |
|  | (1) |

Where,

P = electrical power (in this case 60 Watt, W)

I = electric currents produced by heat source (in this case 40 Ampere, A)

V = potential difference in the electric heat source (in this case 1.5 Volts, V)

Configuration 9 to 16 in Table 4 was modeled by substituting the thermal properties of each material that had been inserted into the properties under wet conditions. Modelling and boundary conditions setup were identical to the simulation for dry conditions. In addition to conductive flow, convective flow was also added to the boundary conditions throughout the system. Convection heat transfer coefficient value of water at room temperature was inserted to ANSYS. The convection heat transfer coefficient may be broken down for convenience into two components as depicted in Equation (2).

|  |  |
| --- | --- |
|  | (2) |

Where,

hc = total convection heat transfer coefficient

hc,n = the portion of convection coefficient accounting for the natural convection phenomenon

hc,f = the portion accounting for the forced convection phenomenon

Natural convection was subjected in this case to represent the natural seepage of the water content in the model without any external mechanisms such as pumps. The natural convective heat transfer coefficient of water in this numerical model was set to 200 W m-2 K-1, a typical value for water at room temperature (Xiao et al., 2018).

### Physical modelling

Marine clay as the CCL was prepared before the physical model setting. The excavated marine clay was transferred to the laboratory storage compartment at Monash University, loaded into trays, oven dried for a minimum duration of 24 hours at 105°C, crushed using a mechanical grinder, and sieved through a 2 mm sieve. There were no settlement, strain or pore pressure measurements during the physical modelling experiment. All the materials and equipment – including the marine clay were put in a wooden box with a dimension of 300 mm x 300 mm x 300 mm. The schematic diagram is shown in Figure 3(a). The locations of the thermocouples are also shown in Figure 3(a). Variations for physical modelling are in conjunction with numerical modelling under dry conditions and are presented in Table 4 (configurations 1-8). Physical modelling in this paper covered dry condition simulation only to validate the effectiveness of utilization of rockwool with different thicknesses. A pressure of approximately 1.5 kPa was applied to ensure the whole system was compacted after setting the materials and equipment inside the box prototype. The pressure was also applied to mimic the pressure from MSW in landfills. However, this pressure was not modeled in ANSYS as stress is considered to have minimal effect on heat exchange properties. The heat pad circuit was set to CET of 40°C and 70°C. The heat pad circuit and data logger were switched on for the experiment until the thermocouple readings stabilized, indicating steady-state conditions. The physical modelling setup of the landfill prototype in the laboratory is shown in Figure 3(b) and the heat application schematic diagram is shown in Figure 4.

|  |
| --- |
|  |
| A machine with wires and a box  Description automatically generated with medium confidence  **(b)** |

Figure 3. (a) Schematic diagram of insulated landfill prototype experiment; (b) Physical modelling of insulated landfill prototype.

A diagram of a circuit

Description automatically generated

Figure 4. Schematic diagram of heat application operation in physical modelling of landfill prototype.

# RESULTS

## Thermal conductivity test results

The reported results of thermal conductivity test were the average of triplicate tests. Table 5 displays typical density and thermal conductivity value of materials that were used in the physical modelling under dry and wet conditions. There was some difference in the measured thermal conductivity of rockwool from existing study. As expected, the materials under wet condition have higher thermal conductivity.

Table 5. Thermal conductivity value of marine clay, rockwool, and sand under dry and wet conditions

|  |  |  |  |
| --- | --- | --- | --- |
| Materials | Typical Density (kg/cm3) (Jayawardane et al., 2021) | Thermal Conductivity Value (W m-1 K-1) | |
| Dry Condition | Wet Condition |
| Marine clay | 1538 | 0.797 | 0.841 |
| Rockwool | 70 | 0.028 | 0.034 |
| Sand | 1499 | 0.253 | 0.264 |

## Numerical and physical modelling differences

The difference between numerical and physical modelling results is shown in Figure 5(a) for CET 40oC and Figure 5(b) for CET 70oC. Figure 5 shows there was a slight difference between the results from numerical and physical modelling. The difference is discussed in latter section. Both modelling results indicated that the temperature dropped as the depth of CCL increased. The physical modelling also validated that the addition of rockwool successfully reduced the CETs inside the landfill liner system and temperature dropped even further when the rockwool insulation was thicker.

|  |  |
| --- | --- |
| (a) | (b) |

## Figure 5. Comparison between numerical and physical modelling of insulated landfill liner under dry conditions with CET of (a) 40°C and (b) 70°C (N = numerical modelling; P = physical modelling).

## Numerical modelling parametric study

Figure 6(a) and (b) portray temperature profiles by ANSYS simulation within CCL depth in the presence of various rockwool thicknesses and moisture conditions in CET of 40 °C and 70 °C, respectively. Temperature profile distribution for all configurations in general was visualized by ANSYS in Figure 7. The numerical results exhibited that the temperature decreased with increasing CCL depth. It was also found that the addition of rockwool as an insulator reduced the CET from the heat source to the landfill liner. Figure 6(a) shows that the presence of rockwool can lower the CET of 40 oC up to 26.41 oC, meanwhile, without rockwool, the CET of 40 oC only dropped up to 34.75 oC. Similarly, rockwool can even lower the greater CET of 70 oC. The CET decreased up to 30.92 oC. The absence of rockwool only decreased the CET of 70 oC up to 41.19 oC.

Additionally, it was discovered that a greater reduction in both CET occurred when the thickness of the rockwool was increased. Take the example of CET 40oC under dry conditions, 20, 35, and 50 mm of rockwool successfully reduced the CET to 28.04, 26.85, and 26.41oC, respectively. The trends happened to all configurations.

The study also revealed that rockwool performed less reduction of CETs in wet conditions. Rockwool with the thickness of 20 mm under dry conditions lowered the CET of 40oC to 28.04oC, meanwhile, the CET only dropped to 29.01oC under wet conditions. This impact of moisture conditions applied to all thicknesses and CETs variations.

|  |  |
| --- | --- |
| (a) | (b) |

Figure 6. Temperature profiles by ANSYS simulation within CCL depth in the presence of various rockwool’s thicknesses and moisture conditions in CET of (a) 40°C and (b) 70°C.

A multicolored cube with a rainbow colored layer

Description automatically generated with medium confidence

Figure 7. Visualization of temperature profile distribution in landfill liner model by ANSYS.

# DISCUSSION

## Numerical and physical modelling differences

The slight differences between numerical and physical modelling that were portrayed in Figure 5 can be calculated using Equation (3) and Equation (4). Meanwhile, the results are tabulated in Table 6. As it can be seen from the table, the temperature differences between the numerical and physical models are not very significant for all variations. This suggests that the ANSYS simulation results are valid based on the supporting physical landfill prototype results. However, some differences still exist between the two methods.

The differences arise due to several factors. The heat transfer considered in ANSYS software is only conduction from the heat source to the CCL and was retained by the insulation material – in this case, rockwool. Meanwhile, the heat flux in the surface area of ​​the landfill other than the surface that was in direct contact with the heat source is considered to be 0 or in a perfectly insulated condition. In the physical model prototype, a wooden box was used to minimize heat transfer between the system and the environment, but the condition was not perfectly insulated as assumed in the numerical model. Another factor that deviated from the ideal assumptions in the numerical model was the non-uniformity of material properties used in the physical model. Additionally, the materials used in the physical model had slight variations in properties, and imperfections were not present in the numerical model. Furthermore, errors in thermocouples due to accuracy and standard deviation in measurement instruments also contributed to the differences. The insignificant differences reflect that rockwool remains effective as a method for heat mitigation in landfill liners. Both methods are still crucial since numerical modelling is efficient for testing the pilot prototype, helps with the trials and errors, and also performs the estimation of the study in a timely manner. On the other side, physical modelling captures the phenomena of variables that are inaccessible by theory, validates the theory, and analyzes the feasibility of the study in various environmental and extreme conditions, especially in waste landfill systems (Carmo, 2020).

|  |  |
| --- | --- |
|  | (3) |
|  | (4) |

Where,

= Average temperature differences

= Average temperature results from numerical modelling

= Average temperature results from physical modelling

= Average temperature difference percentages

Table 6. Temperature differences between numerical and physical models for insulated landfill liners exposed to CET

|  |  |  |  |
| --- | --- | --- | --- |
| CET (oC) | Rockwool thickness (mm) | (oC) | (%) |
| 40 | 0 | 1.23 | 3.25 |
| 20 | 0.26 | 0.88 |
| 35 | 0.46 | 1.66 |
| 50 | 0.96 | 3.60 |
| 70 | 0 | 0.77 | 1.43 |
| 20 | 1.10 | 2.62 |
| 35 | 0.03 | 0.07 |
| 50 | 0.47 | 1.46 |

## Effect of insulation’s thickness on temperature within the CCL

The temperature profiles in all configuration variations exhibited similar behavior: the temperature decreased as the CCL distance from the heat source increased. The trends were proven by Figure 5 and Figure 6. The addition of rockwool as an insulation layer lowered the temperature within the CCL. It can be identified that in general rockwool was effective in reducing the ETs in the landfill liner. The effectiveness of rockwool as a heat mitigation method is caused by two main reasons. First, rockwool has low thermal conductivity to minimize the conductive heat transfer from the system to the environment. Effective thermal insulation typically has a thermal conductivity value below 0.1 W m-1 K-1 (Karaaslan et al., 2016). Table 5 showsthe thermal conductivity value of rockwool already fulfills the requirement. Second, rockwool has a porous structure that can trap air inside the structure (Lu et al., 2019). Allowing air pockets to form inside the structure of a material leads to the reduction of heat transfer by conduction and radiation (Clarke et al., 2017).

Furthermore, the temperature reduction percentages (TRPs) were calculated for each rockwool’s thickness to analyze the effect of insulation thicknesses on mitigating ETs in landfill liners. TRPs were calculated by using Equation (5) and are shown in Figure 8. The mean TRP increasing rate (MTIR) was also computed by following Equation (6) to evaluate the significance of rockwool thicknesses on lowering the temperature within the CCL system. The summary of MTIR of each rockwool’s thickness is tabulated in Table 7 and Table 8.

|  |  |
| --- | --- |
|  | (5) |
|  | (6) |

Where,

TRP = Temperature reduction percentage

TI = Temperature of CCL in the presence of insulation

T0 = Temperature of CCL without insulation

MTIR = Mean temperature increasing rate

= Mean of temperature reduction percentage after increment of rockwool’s thickness

= Mean of temperature reduction percentage before increment of rockwool’s thickness

x1 = thickness of rockwool before increment of the insulation

x2 = thickness of rockwool after increment of the insulation

|  |  |
| --- | --- |
| (a) | (b) |

Figure 8. TRPs by ANSYS simulation within CCL depth in the presence of various rockwool thicknesses and moisture conditions in CET of (a) 40°C and (b) 70°C.

Table 7. MTIR calculated for the CCL exposed to 40°C CET in the presence of different rockwool thicknesses and moisture conditions

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Rockwool thickness (mm) | | Mean of TRP (%) | | MTIR (%/mm) |
| Before Increment | After Increment | Before Increment | After Increment |
| 0 | 20 | 0 | 20.75 | 1.04 |
| 20 | 35 | 20.75 | 26.43 | 0.38 |
| 35 | 50 | 26.43 | 28.32 | 0.13 |

Table 8. MTIR calculated for the CCL exposed to 70°C CET in the presence of different rockwool thicknesses and moisture conditions

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Rockwool thickness (mm) | | Mean of TRP (%) | | MTIR (%/mm) |
| Before Increment | After Increment | Before Increment | After Increment |
| 0 | 20 | 0 | 19.62 | 0.98 |
| 20 | 35 | 19.62 | 34.87 | 1.02 |
| 35 | 50 | 34.87 | 38.81 | 0.26 |

It can be observed from Figure 8(a) that the presence of rockwool with thicknesses of 20, 35, and 50 mm reduced the temperature within the CCL in the range of 17.66 – 24.59%, 27.73 – 30.36%, and 23.26 – 32.47%, respectively. The increase in TRP as the rockwool thickness increases indicate that thicker rockwool is more effective in reducing CET of 40oC or average ETs during waste generation in the landfill system. The same phenomena happened to the CET of 70 oC cases that is portrayed in Figure 8(b). Temperature in the CCL was decreased by 8.09 – 28.43%, 23.17 – 42.38%, and 24.32 – 48.45% while being insulated with 20, 35, and 50 mm rockwool, respectively. However, calculations in Table 7 display that MTIR for the thicker layer of rockwool was not significant when compared with the MTIR value of the thinner layer. It can be deduced that a rockwool thickness of 20 mm was sufficient to suppress the heat flow from 40°C CET. In contrast, the data in Figure 8(b) and Table 8 show that 20 mm rockwool struggled to mitigate heat from CET of 70oC, which represents extreme ETs generated by waste in the landfill liner. A thicker layer of rockwool is needed to lower the ETs in the landfill liner model. Rockwool with thicknesses of 35 mm and 50 mm were still effective in attenuating the 70oC CET, those rockwools were able to make the temperature from the heat source drop from the CET of 70oC, even up to 30.92oC. The CCL temperature of 30.92oC can be categorized as “safe” since CCL temperatures above 35°C are generally considered ETs that bring negative impact to the liner (Yoshida and Rowe, 2003).

## Effect of moisture content on the effectiveness of thermal insulation in landfill liner

Table 5 is an indication that moisture content existence increased the thermal conductivity and led to reduced effectiveness of the insulation process. This is because water typically has a higher thermal conductivity than air. When a material is wet, the water within it can transfer heat more efficiently than the air that would be present in dry conditions.

Figure 6 and Figure 8 further demonstrate the correlation between moisture conditions and the effectiveness of rockwool in reducing the CET in CCL. Variations of 20 mm rockwool are examples in this case, that insulation in dry conditions was able to attenuate the CET of 40oC by 19.30 – 24.59%, meanwhile, wet insulation only decreased the temperature in the range of 17.66 – 20.21%. This occurred at all variations in insulation thicknesses and both CETs.

Several factors contribute to the reduced effectiveness of insulation due to the moisture content. Firstly, thermal conductivity increases with higher water content. A study revealed that rockwool’s thermal conductivity can increase up to 40% in the presence of 35% water content (Hung Anh and Pásztory, 2021). Secondly, the natural porous structure of rockwool allows it to easily absorb water. Water fills the air pockets that should be captured by rockwool in a dry state and replaces air which is an insulator (Yap et al., 2021). On the other side, rockwool is also easy to dry which can be beneficial in landfill applications. The third reason is the property of moisture itself. Water has higher thermal conductivity than most solid materials, including rockwool (Huber et al., 2012). Higher thermal conductivity refers to the ability of a material to transfer heat more rapidly. In addition to moisture content, typical density value may also affect thermal insulation performance since greater density of CCL increases particle interaction and decreases air gaps. On the other hand, rockwool’s insulating qualities depend on the preservation of air pockets inside its structure (Lu et al., 2019). Despite these challenges, an insulated landfill model under wet conditions can still mitigate heat within the CCL in the landfill liner.

# CONCLUSION

The numerical and physical modelling conducted in this study aimed to evaluate the effectiveness of rockwool with various thicknesses as thermal insulation materials for landfill liner applications under different CETs and moisture conditions. Based on the numerical results, rockwool proved effective as a thermal insulation material in landfill liners. However, a thinner layer of rockwool was effective in reducing the average ETs. In contrast to that, a thicker layer of rockwool was needed to successfully mitigate extreme ETs conditions. Under wet conditions, which are common in real landfill situations, the effectiveness of rockwool in reducing CET was diminished. However, the temperature range that had been mitigated was still categorized as a safe temperature below 35oC (Yoshida and Rowe, 2003). The effectiveness of rockwool in landfill liners was validated by physical prototype testing, which showed minor differences from the numerical modelling outcomes. In conclusion, rockwool has been proven to be effective under various conditions and promotes material sustainability.

It is crucial to consider local regulations and cost-effectiveness while selecting insulation material. However, this study primarily focused on the thermal response of rockwool liners for landfill applications in marine clay. Future studies could explore the long-term performance of insulated liner and T-H-M response of rockwool liners in detail, including thermal stress development, deformation behavior, and geotechnical stability. Furthermore, exploring alternative environmentally friendly materials with similar thermal insulation capabilities and conducting a cost-benefit analysis would enhance the applicability and sustainability of insulation materials for landfill liners.

DISCLAIMER

The authors declare no conflict of interest.

AVAILABILITY OF DATA AND MATERIALS

All data are available from the author.

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