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Influence of Soil Gradation, Moisture Content, And Density on Thermal Resistivity of Soils in Backfill Applications

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Abstract - Efficient heat dissipation is critical for the ampacity and longevity of underground power transmission systems, yet the dynamic thermal behavior of backfill soils under changing environmental conditions remains under-characterized. The primary objective of this study is to quantify the influence of particle gradation, compaction density, and atmospheric drying on the thermal resistivity of sandy backfills to optimize trench design. Laboratory investigations were conducted on poorly graded (SP) and well-graded (SW) sands using the Transient Line Source (TLS) method. Tests evaluated varying relative densities (20%, 50%, and 80%) and moisture contents (0%–8%), along with a dynamic simulation of construction-phase delays in which samples were exposed to atmospheric drying for 24 hours. Results indicate that well-graded sand consistently exhibits 10–15% lower thermal resistivity than poorly graded sand due to superior particle packing mechanics. While increasing moisture to the critical threshold of 8% drastically reduced resistivity to ranges of 0.489–0.640 K.m/W (SP) and 0.389–0.543 K.m/W (SW), atmospheric exposure caused a rapid degradation in performance, with resistivity spiking by 123–158% within 24 hours due to the rupture of hydraulic bridges. A multilinear regression model incorporating these variables achieved high predictive accuracy (R^2 = 0.97, RMSE = 0.089 K.m/W). These findings provide a robust framework for selecting backfill materials and predicting thermal risks during installation, ultimately enhancing the reliability of underground cable networks.

Keywords: T*hermal resistivity, Sand backfill, Buried cables, Moisture content, Atmospheric exposure, Regression modelling*

1. INTRODUCTION

In the rapidly evolving landscape of power distribution and underground utility systems, the thermal performance of cable trench backfill materials has become a critical factor in ensuring the operational efficiency and longevity of buried power cables. Among the various parameters influencing cable performance, the thermal resistivity of the surrounding soil, a measure of its resistance to heat flow, plays a pivotal role [1-2]. When electrical power flows through underground cables, it inevitably generates heat, which must be effectively dissipated into the surrounding soil to prevent thermal overloading. If the thermal resistivity of the backfill is underestimated or improperly accounted for, the heat generated cannot escape efficiently [3-5]. As a result, cable temperatures may rise beyond safe operational limits, potentially leading to premature insulation failure, reduced current-carrying capacity (ampacity), and, in extreme cases, complete cable burnout [6]. Such failures are costly to repair and can lead to significant service interruptions and safety hazards.

To mitigate these risks, engineers rely on accurate thermal resistivity measurements to design appropriate cable trench environments. However, soil thermal resistivity is not a fixed property; rather, it is a dynamic parameter significantly influenced by soil density, sand gradation, and moisture content [7-9]. Early studies, such as those by Gouda et al. [10], incorporated these variations into thermal models per IEC 60853-2. More recently, Wu et al. [11] investigated ten compacted backfill soils, finding that compaction increased thermal conductivity by 20–50%, driven primarily by quartz content, and proposed prediction formulae based on dry density and moisture content. Similarly, laboratory studies on Jordanian soils [12] and other granular matrices [13] confirmed that thermal conductivity increases rapidly with moisture content up to a threshold (~27%), attributing this behavior to the formation of water films that enhance inter-particle heat transfer.

Beyond basic physical states, recent research has highlighted the importance of microstructural mechanisms. A few researchers, Xu et al. [14, 15], demonstrated that for engineering barrier systems and natural soils, the evolution of thermal properties is heavily dependent on multiphysical coupling (temperature and drying-wetting cycles) and cementation agents. These perspectives suggest that microstructural force chains are key intrinsic mechanisms controlling thermal resistivity. Concurrently, researchers have sought to optimize backfill through alternative materials. Sah and Kumar [16] demonstrated that modifying bentonite with fly ash or sand significantly enhances thermal conductivity while mitigating shrinkage. Similarly, Li et al. [17] and Dinh et al. [18]

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Vol. 15 Issue 04 , April - 2026

validated the use of enzyme-induced carbonate precipitation (EICP) and prepacked aggregate concrete, respectively, to achieve superior thermal performance.

While these novel additives offer specific improvements, characterizing the combined effects of natural soil variables remains paramount to ensure practical applicability across diverse ground conditions. Although the relationships among soil density, moisture, and thermal conductivity are documented in classical literature, existing studies predominantly focus on static conditions, with few examining the combined effect of these parameters [19]. Furthermore, while substantial research has established correlations between soil index properties and electrical resistivity [20], comprehensive models linking basic soil parameters to thermal conductivity in cable backfills remain underdeveloped.

A critical limitation in the current body of work is the neglect of dynamic environmental exposure. The existing literature largely assumes that moisture content is a fixed parameter during the measurement period; consequently, there is a paucity of data addressing the rate of thermal degradation when backfill materials are subjected to rapid atmospheric drying, a common scenario during the 'open trench' phase of cable installation. Specifically, the comparative performance of Poorly Graded (SP) versus Well Graded (SW) sands under these transient conditions remains underexplored. This study aims to bridge this gap by systematically investigating the combined effect of sand gradation, compaction, and time-dependent atmospheric exposure. By quantifying the rate of performance degradation as liquid bridges rupture, this work moves beyond static characterization to provide actionable data on the temporal stability of backfills, which is critical for determining installation timelines and field quality control protocols.

2. MATERIALS USED

Two types of sand with distinct gradation characteristics were selected and procured for the experimental study to investigate the effect on soil thermal resistivity. These samples were selected to represent the distinct boundaries of standard engineering classification: Sample 1 represents a typical uniform Poorly Graded Sand (Cu=4). In contrast, Sample 2 represents a typical Well Graded Sand (Cu=9) with a broad particle distribution. The selected sand samples were characterised in accordance with Indian Standards to determine their fundamental geotechnical properties, including particle-size distribution, maximum and minimum dry densities, and the angle of internal friction. The gradation curves of both samples are shown in Fig. 1.

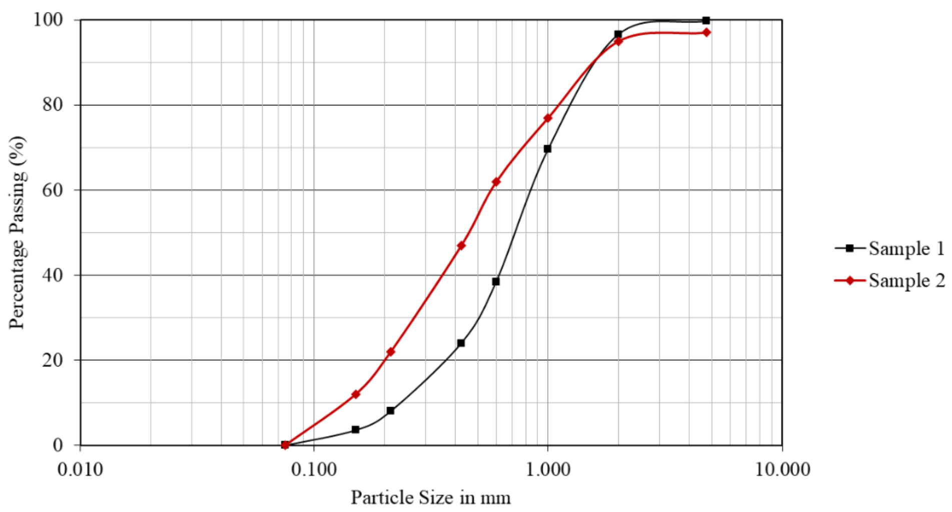

Fig. 1 Grain Size Distribution Analysis of Samples

The grain size analysis indicates that Sample 1 is classified as poorly graded sand (SP), while Sample 2 is classified as well-graded sand (SW). The additional properties of the samples are provided in Table 1.

International Journal of Engineering Research & Technology (IJERT)
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Vol. 15 Issue 04 , April - 2026

Table 1. Properties of the Soil Samples

Properties	Sample 1	Sample 2
Coefficient of Uniformity (Cu)	4	9
Coefficient of Curvature (Cc)	1	1.5
Soil Classification	SP	SW
Maximum density (g/cc)	1.708	1.820
Minimum density (g/cc)	1.424	1.55
The angle of Internal Friction (ϕ)	34	38

2.1 Thermal Resistivity Test

The thermal resistivity of the specimens was measured using the TLS-100 Portable Thermal Conductivity Meter (Fig. 2) (Thermtest Inc., Canada), based on the Transient Line Source (TLS) method. The instrument employs a needle probe containing both a heating element and a temperature sensor, inserted directly into the sample. A known heat pulse is applied, and the resulting temperature rise is recorded over time. Thermal conductivity is determined by fitting the temperature-time response to the theoretical model of transient heat conduction. The TLS-100 is capable of measuring a wide range of materials, including soils, pastes, powders, and solids, with a typical accuracy of ±5%. Its portability and ease of operation make it particularly suitable for both laboratory and field applications.

Fig. 2 TLS-100 Portable Thermal Conductivity Meter

3. EXPERIMENTAL PROGRAMME

The experimental study was designed to systematically investigate the thermal resistivity behaviour of granular soils under varying conditions of density, moisture content, and atmospheric exposure time. Two types of sand were selected based on their gradation characteristics: poorly graded sand (SP) and well-graded sand (SW). Initially, both soil types were tested in their dry state under three distinct compaction levels, dense, medium dense, and loose, to evaluate the influence of relative density on thermal resistivity.

Subsequently, each gradation type and density condition was tested after the controlled addition of 2%, 4%, 6%, and 8% water content by dry weight to assess the effect of moisture content. The maximum moisture content was limited to 8% to align with the field capacity of the selected granular materials. Due to the high permeability and low fines content of clean SP and SW sands, they are free-draining and rarely retain moisture exceeding 8% under gravitational drainage in typical trench environments. Consequently, testing beyond this limit would simulate submerged or slurry conditions, which are outside the scope of typical backfill design parameters. To ensure measurement reliability, the thermal probe was calibrated against standard reference materials (polymer) prior to testing, and inserted using a standardized guide to minimize contact resistance. All experiments were conducted

International Journal of Engineering Research & Technology (IJERT)
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Vol. 15 Issue 04 , April - 2026

in a controlled environment (25° ± 1°C, 60 ± 5% RH), with three replicates per condition recorded only after the samples reached thermal equilibrium.

Following this, the specimens at all three density levels were prepared with 8% water content, sealed, and then simultaneously exposed side-by-side to ambient atmospheric conditions (38-40°C). During this period, ambient relative humidity was monitored using a digital hygrometer to ensure consistent environmental baselines. To ensure data accuracy, samples were temporarily shielded from wind and direct sunlight during the specific 180-second data acquisition intervals. This prevented rapid convective cooling or surface temperature fluctuations from distorting the probe's thermal pulse. This exposure phase was designed to simulate the short-term "open trench" conditions encountered during construction, during which backfill material is often left exposed to the environment before the final installation of cover slabs or paving. A duration of 24 hours was selected as the representative maximum time window for such construction delays. Thermal resistivity measurements were taken at 2, 4, 8, and 24 hours to quantify the rapid degradation of thermal properties due to evaporative moisture loss during this critical installation phase. Moisture content was also recorded at each time interval to correlate with changes in resistivity. This stepwise, parameter-isolated approach provided a robust dataset for understanding the thermal resistivity response under varied field-simulated conditions. The detailed test matrix is shown in Table 2.

Table 2 Test Matrix of the Experimental Programme

Phase	Objective	Soil Type	Density Condition	Moisture Content (%)	Exposure Time (hrs)	Thermal Resistivity Measured	Moisture Content Monitored
Phase 1	Effect of Dry Density	SP, SW	Dense, Medium, Loose	0 (Dry)	-	Yes	No
Phase 2	Effect of Moisture Content	SP, SW	Dense, Medium, Loose	2, 4, 6, 8	-	Yes	No
Phase 3	Effect of Atmospheric Exposure (drying)	SP, SW	Dense, Medium, Loose	8 (initially)	2, 4, 8, 24	Yes	Yes

4. RESULTS AND DISCUSSION

The experimental investigations were carried out in a controlled laboratory environment, in strict accordance with the operational protocols outlined in the equipment manuals to ensure consistency and reliability. The data acquired from the tests underwent rigorous analysis, carefully considering potential variabilities. The findings are critically interpreted and systematically discussed in the following sections.

4.1 Effect of Density

As outlined in the previous section, both soil types were compacted at different relative densities within a 1000 ml capacity mould. Subsequently, thermal resistivity tests were conducted on each prepared specimen. Figure 3 depicts the testing of thermal resistance using the TLS-100 Portable Thermal Conductivity Meter in the compacted soil. The results are analysed and drawn in a graph as presented in Figure 4.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

Fig. 3 Conducting Test in a Compacted Soil Mould

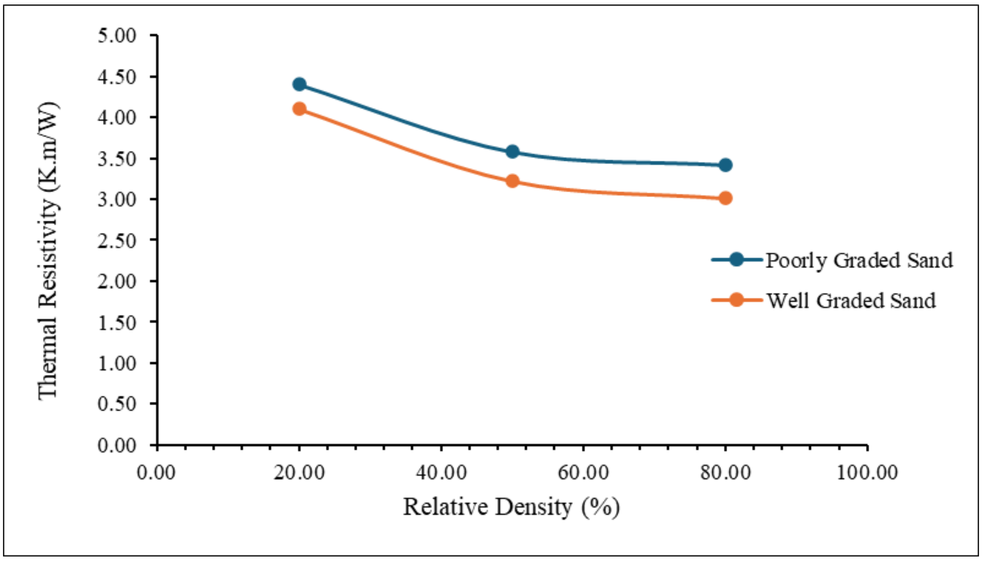

Fig. 4 Thermal Resistivity of Sand with Various Relative Densities

Thermal resistivity in well-graded sand is found to be lower than in poorly graded sand, regardless of relative density, due to its superior particle size distribution and packing efficiency. Well-graded sand, characterised by a diverse range of particle sizes, enables smaller particles to fill voids between larger ones, enhancing inter-particle contacts and creating efficient heat transfer pathways [21-22]. The superior thermal performance of well-graded (SW) sand compared to poorly graded (SP) sand is fundamentally rooted in particle packing mechanics. Heat transfer in dry granular media occurs primarily through solid-to-solid contact points; however, these points act as thermal throttles due to high constriction resistance at the narrow interfaces. In poorly graded sand (SP), the uniformity of particle sizes results in a lower coordination number (the average number of contact points per particle). Even at high relative densities, the lack of intermediate-sized particles leaves significant interstitial void volumes filled with air, which acts as a thermal insulator (0.026 W/m·K). Conversely, the diverse particle size distribution of well-graded sand (SW) allows for Apollonian packing, where smaller grains occupy the voids created by larger grains. This has two mechanistic effects: Increased Coordination Number: The presence of finer particles creates additional contact points, bridging gaps between larger particles and forming a denser network of solid thermal pathways. Void Displacement: Solid particles (≈7.0 W/m·K for quartz) physically displace insulating air volume. Therefore, the 10–15% lower resistivity observed in SW sand is not merely due to density, but due to the geometric optimization of the heat flow lattice, which minimizes the reliance on conduction through the air phase.

4.2 Effect of Moisture Content

To investigate the influence of moisture content on the thermal resistivity of soil, experiments were conducted using both poorly graded and well-graded sands. Each sand type was prepared with varying moisture contents of 2%, 4%, 6%, and 8% by weight

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Vol. 15 Issue 04 , April - 2026

relative to its dry mass. The soil samples were also compacted to different relative density levels to assess the combined effects of moisture and density on thermal resistivity. This systematic approach enabled a comprehensive evaluation of how moisture content interacts with soil gradation and packing characteristics to influence thermal conduction properties. The testing system is presented in Figure 5.

Fig. 5 Representative Experimental Setup for Thermal Resistivity Testing across Varying Moisture Contents

Thermal resistivity measurements were obtained for poorly graded and well-graded sands using specialised laboratory equipment to evaluate the effect of moisture content on the thermal resistivity of soil. Each sand type was tested at moisture contents of 2%, 4%, 6%, and 8% by weight relative to its dry mass, with samples prepared at varying relative density levels to assess the interplay of moisture and packing characteristics. Thermal resistivity values were recorded in triplicate for each combination of moisture content and relative density, and the results were averaged to ensure reliability and minimise experimental error [21]. The averaged data were analysed to compare the thermal resistivity trends between poorly graded and well-graded sands across the tested conditions. Figures 6 and 7 graphically illustrate the relationships among moisture content, relative density, and thermal resistivity for poorly graded (SP) and well-graded (SW) sands. These figures highlight the effects of soil gradation and moisture content on thermal conduction properties. Corresponding thermal resistivity values for SP and SW sands, as functions of varying moisture content, are presented in Tables 3 and 4, respectively.

Table 3 Variation in Thermal Resistivity due to Moisture Content in SP Soil

Relative density (%)			20		
Moisture Content (%)	0	2	4	6	8
Thermal resistivity (K.m/W)	4.401	2.52	1.646	1.069	0.640
Relative density (%)			50		
Moisture Content (%)	0	2	4	6	8
Thermal resistivity (K.m/W)	3.580	2.190	1.340	0.820	0.501
Relative density (%)			80		
Moisture Content (%)	0	2	4	6	8
Thermal resistivity (K.m/W)	3.420	1.954	1.274	0.824	0.489

International Journal of Engineering Research & Technology (IJERT)
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Vol. 15 Issue 04 , April - 2026

Table 4 Variation in Thermal Resistivity due to Moisture Content in SW Soil

Relative density (%)			20		
Moisture Content (%)	0	2	4	6	8
Thermal resistivity (K.m/W)	4.100	2.125	1.394	0.912	0.543
Relative density (%)			50		
Moisture Content (%)	0	2	4	6	8
Thermal resistivity (K.m/W)	3.220	1.864	1.210	0.795	0.455
Relative density (%)			80		
Moisture Content (%)	0	2	4	6	8
Thermal resistivity (K.m/W)	3.010	1.659	1.084	0.698	0.389

It is noted that the thermal resistivity values for dry sands (0% moisture) are relatively high, ranging from 4.40 K.m/W in the loose state to 3.01–3.42 K.m/W in the dense state (Tables 3 and 4). These values reflect the effective thermal resistivity of the bulk material, where the high constriction resistance at the dry particle contacts severely limits heat transfer.

While increasing the relative density to 80% reduced the resistivity by approximately 20–25%, confirming the beneficial effect of increased particle coordination, it did not reduce the resistivity to typical field levels (0.5–1.5 K.m/W). This confirms that, without the formation of liquid bridges to widen thermal pathways, densification alone has limited ability to lower the resistivity of completely dry granular media. These values represent the realistic upper bound for these specific sand gradations under strict zero-moisture conditions.

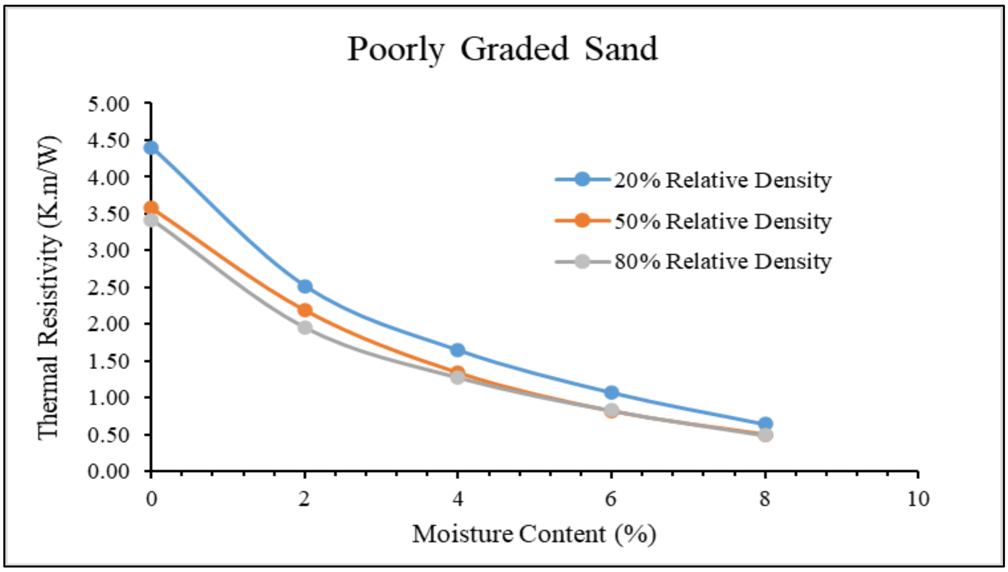

Fig. 6 Thermal Resistivity Reduction with respect to Moisture Content on SP Sand

International Journal of Engineering Research & Technology (IJERT)
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Vol. 15 Issue 04 , April - 2026

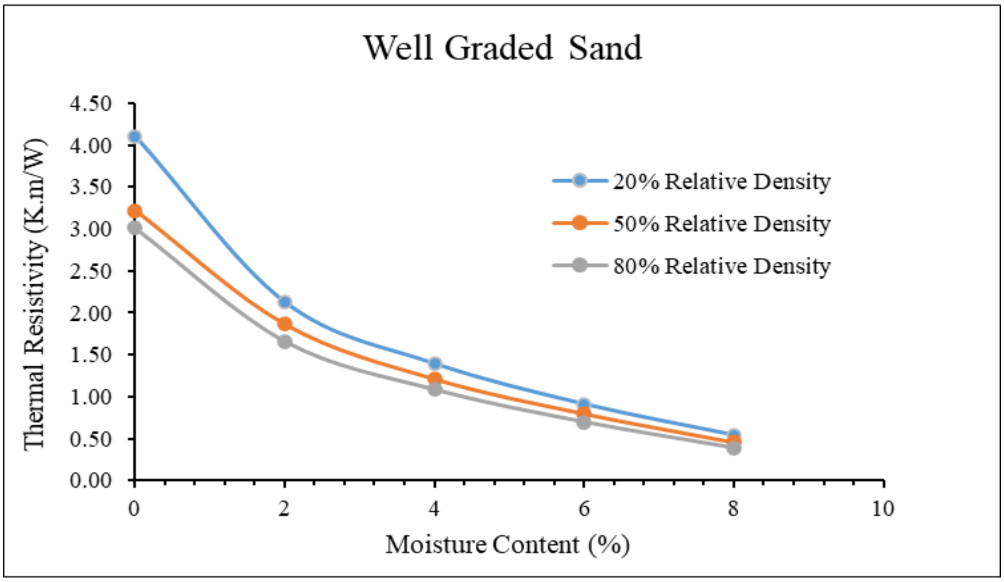

Fig. 7 Thermal Resistivity Reduction with respect to Moisture Content on SW Sand

The thermal resistivity of poorly graded (SP) and well-graded (SW) sands decreases significantly with increasing moisture content, as observed across relative density levels of 20%, 50%, and 80%. For SP sand, thermal resistivity drops from 4.401 K.m/W at 0% moisture to 0.640 K.m/W at 8% moisture for a relative density of 20%, with similar trends at higher density levels (Tables 3 and 4). For SW sand, the values are consistently lower, ranging from 3.732 K.m/W at 0% moisture to 0.543 K.m/W at 8% moisture for the same density, reflecting a reduction of approximately 15% compared to SP sand. This reduction is attributed to the enhanced particle packing in SW sand, which minimises air voids and facilitates thermal conduction. The combined effect of density and moisture content is pronounced: at higher densities (80%) and moisture content (8%), SW sand exhibits a thermal resistivity of 0.417 K.m/W, compared to 0.489 K.m/W for SP sand, indicating that increased density amplifies the moisture-induced reduction in thermal resistivity by improving inter-particle contacts and reducing insulating air gaps. These trends underscore the critical interplay between soil gradation, density, and moisture in optimising thermal performance for applications such as underground cable systems. The micromechanics of liquid bridging can explain the dramatic reduction in thermal resistivity with the addition of moisture. At low moisture contents (2–4%), the soil exists in the pendular regime. In this state, water is held primarily at the particle contact points by capillary forces, forming liquid bridges or menisci. Since water (0.6 W/m.K) is approximately 23 times more thermally conductive than air (0.026 W/m.K), these liquid rings effectively increase the thermal contact area around the grain-to-grain contact points. This drastically reduces the constriction resistance that dominates heat transfer in dry soil. The sharpest drop in resistivity observed between 0% and 4% moisture (Fig. 6 and 7) corresponds to the rapid establishment of these bridges. As moisture increases to 8% (transitioning toward the funicular regime), the water films merge to fill the larger pore spaces. While this continues to lower resistivity by replacing bulk air with water, the rate of improvement diminishes once the primary particle contacts are fully bridged. The SW sand consistently outperforms SP sand in this regard because its smaller average pore size generates stronger capillary forces, maintaining the integrity of these liquid bridges more effectively than the larger pores of SP sand.

4.3 Effect of Atmospheric Exposure

To investigate the influence of atmospheric exposure on the thermal resistivity of sands, a series of tests was conducted on poorly graded (SP) and well-graded (SW) sands prepared at relative density levels of 20%, 50%, and 80%, with a range of moisture contents of 8%, 4% and 2%. The samples were exposed to natural sunlight for durations of 2, 4, 8, and 24 hours to simulate environmental conditions (Fig. 8) that may alter soil properties, such as moisture loss or surface compaction, thereby affecting thermal conduction. This study is critical for applications like underground cable systems, where prolonged exposure to atmospheric conditions can impact heat dissipation efficiency. Tables 5 and 6 present the values of varying thermal resistivity, and Figures 9 and 10 represent the graphical representation of thermal resistivity variation based on atmospheric exposure of SP and SW sands.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

Fig. 8 Samples Kept under Direct Atmospheric Exposure

Table 5 Variation in Thermal Resistivity due to Atmospheric Exposure in SP Soil

Thermal resistivity (K.m/W)									
Exposure	**8% Moisture Content**			**4% Moisture Content**			**2% Moisture Content**		
Time (hr)	**20% Dense**	**50% Dense**	**80% Dense**	**20% Dense**	**50% Dense**	**80% Dense**	**20% Dense**	**50% Dense**	**80% Dense**
0	0.64	0.501	0.489	1.11	0.982	0.935	2.245	2.07	1.960
2	0.922	0.791	0.736	1.524	1.278	1.189	2.345	2.154	2.035
4	1.141	1.002	0.922	1.775	1.458	1.343	2.416	2.217	2.083
8	1.463	1.311	1.193	2.02	1.632	1.493	2.503	2.289	2.136
24	1.43	1.291	1.162	2.16	1.732	1.579	2.6	2.34	2.176

Table 6 Variation in Thermal Resistivity due to Atmospheric Exposure in SW Soil

Thermal resistivity (K.m/W)									
Exposure	**8% Moisture Content**			**4% Moisture Content**			**2% Moisture Content**		
Time (hr)	**20% Dense**	**50% Dense**	**80% Dense**	**20% Dense**	**50% Dense**	**80% Dense**	**20% Dense**	**50% Dense**	**80% Dense**
0	0.544	0.427	0.403	0.944	0.837	0.771	1.908	1.764	1.615
2	0.786	0.671	0.626	1.299	1.084	1.011	1.999	1.827	1.731
4	0.958	0.675	0.785	1.49	0.982	1.143	2.029	1.493	1.773
8	1.251	1.11	0.996	1.727	1.382	1.248	2.14	1.938	1.785
24	1.216	1.099	0.945	1.837	1.474	1.284	2.211	1.992	1.770

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Vol. 15 Issue 04 , April - 2026

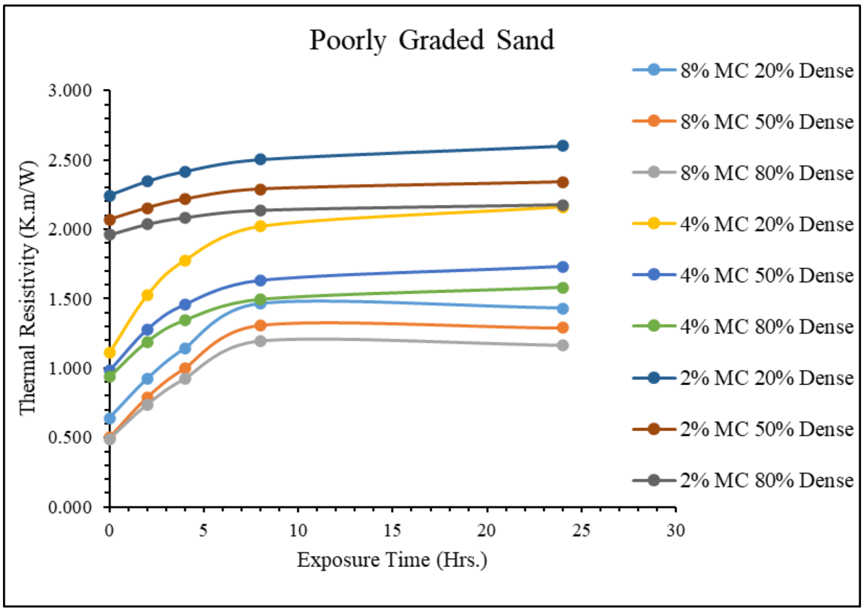

Fig. 9 Thermal Resistivity Variation due to Atmospheric Exposure Time in SP Sand

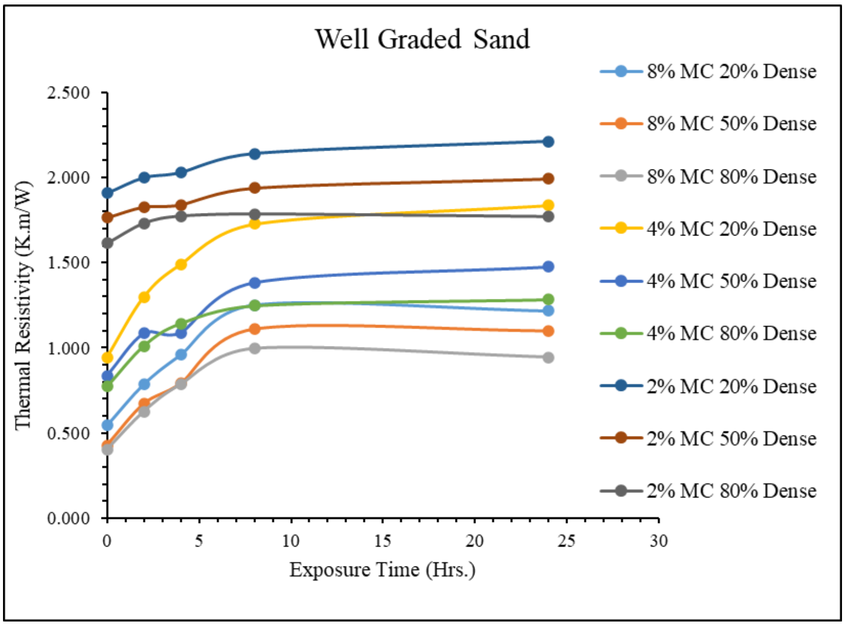

Fig. 10 Thermal Resistivity Variation due to Atmospheric Exposure Time in SW Sand

The thermal resistivity of poorly graded (SP) and well-graded (SW) sands is strongly influenced by atmospheric exposure, governed by initial moisture content, relative density, and soil gradation. The study reveals how moisture loss and particle arrangement jointly affect heat transfer in these soils. The rapid increase in thermal resistivity during atmospheric exposure, particularly in samples with high initial moisture (8%), is driven by the physics of evaporation in porous media.

Rupture of Liquid Bridges: As evaporation proceeds, the retreating water front causes the rupture of the continuous liquid films connecting the particles. Once the hydraulic connectivity is broken, the heat transfer mechanism is forced to revert from efficient conduction through the liquid phase back to inefficient point-to-point solid conduction.

Hysteresis Effect: The data shows a non-linear response where resistivity rises sharply in the first 8 hours (Fig. 9 & 10). This corresponds to the constant rate period of drying, where water evaporates from the surface, creating a “dry crust” of high thermal resistivity at the top of the sample. This dry surface layer acts as a thermal barrier, impeding heat flow from the probe even if the bulk soil underneath retains some moisture.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

In SW sands, the higher capillary potential created by fines helps draw internal moisture to the surface, potentially delaying the complete drying of the surface layer compared to SP sands, which explains the slightly more stable resistivity trends observed in SW samples during the early hours of exposure.

This observation of time-dependent resistivity scaling provides a novel operational constraint for site engineers. The data indicate that for SP sands, a delay of just 4 hours in covering the trench can result in a thermal resistivity increase of over 75% (Table 5), a factor rarely accounted for in static design specifications.

4.3.1 Influence of Initial Moisture Content

At high moisture (8%), both sands show a significant increase in resistivity (123–158%) over 24 hours due to evaporation disrupting conductive moisture films. Initial resistivity values are low (0.40–0.64 K.m/W for SP, 0.40–0.54 for SW). At moderate moisture (4%), resistivity rises moderately (69–95%) with initially higher values (0.77–1.11 K.m/W), reflecting reduced moisture and a mixed conduction regime. At low moisture (2%), Resistivity changes little (10–16%) and remains high (1.61–2.25 K.m/W) as air-filled voids dominate and moisture equilibrium is reached.

4.3.2 Effect of Relative Density

Increasing density consistently lowers resistivity due to better particle contact, enhancing solid conduction. This effect is more pronounced at lower moisture levels, where solid conduction dominates.

4.3.3 Gradation Effects

SW sand exhibits consistently lower Resistivity than SP sand across moisture and density levels, owing to improved particle packing and reduced void space. SW sand also shows slightly more stable resistivity trends during exposure.

4.3.4 Temporal Behaviour and Implications

Thermal resistivity rises rapidly in the first 8 hours of exposure, then stabilises or slightly decreases by 24 hours, indicating moisture redistribution. These findings highlight the critical impact of atmospheric exposure on thermal properties, especially for moist soils, with important implications for geotechnical thermal applications requiring moisture control.

5. PREDICTIVE MODEL FOR THERMAL RESISTIVITY AS A FUNCTION OF MOISTURE, DENSITY, AND EXPOSURE

A multilinear regression analysis was conducted to develop a predictive equation for the thermal resistivity of both SP and SW sands, explicitly considering initial moisture content, relative density, and atmospheric exposure time. The experimental dataset comprised 90 data points spanning moisture contents of 2%, 4%, and 8%; relative densities of 20%, 50%, and 80%; and exposure intervals of 0, 2, 4, 8, and 24 hours. To capture the non-linear and interaction effects among variables, a quadratic polynomial regression model was fitted with main effects and interaction terms for sand type (SP = 0, SW = 1), initial moisture content (M, %), relative density (D, %), and exposure (T, hr). The resulting equation is:

$$K = 3.459 - 0.193S - 0.642M - 0.012D + 0.085T - 0.193S^2 + 0.030SM + 0.0005SD - 0.003ST + 0.040M^2 + 0.0004 + 0.002MT + 0.00006D^2 - 0.0001DT - 0.0027T^2 \text{ ---------(1)}$$

Where:

K: predicted thermal resistivity (K.m/W)

S: sand type (0 for SP, 1 for SW)

M: initial moisture content (%)

D: relative density (%)

T: exposure time (hr)

The regression model agreed strongly with the experimental data ($R^2 = 0.97$, RMSE = 0.089 K.m/W, mean absolute error ≈ 5.5%).

The predictive equation can be directly implemented or embedded in analysis tools. A Python function for practical calculations is provided below:

```python
def predict_thermal_resistivity(sand_type, moisture_content, density, exposure_time):
    """
    Predict thermal resistivity (m.K/W) of SP or SW sand using the regression model.
      Parameters:
      sand_type (int): 0 for SP (Poorly graded), 1 for SW (Well graded)
      moisture_content (float): Initial moisture content (%)
      density (float): Relative density (%)
      exposure_time (float): Atmospheric exposure time (hours)
      Returns:
      float: Predicted thermal Resistivity (m.K/W)
    """
    # Regression coefficients (match the equation shown in the manuscript section)
    coefficients = [-0.193225, -0.642097, -0.012176, 0.085377, -0.193225,
                    0.030102, 0.000456, -0.003451, 0.040129, 0.000402,
                    0.001996, 0.000059, -0.000137, -0.002655]
    intercept = 3.459321
    S = sand_type
    M = moisture_content
    D = density
    T = exposure_time
    features = [S, M, D, T, S**2, S*M, S*D, S*T, M**2, M*D, M*T, D**2, D*T, T**2]
    # Linear combination
    theta = intercept + sum(coef * val for coef, val in zip(coefficients, features))
    return theta

# Example usage
result = predict_thermal_resistivity(sand_type=0, moisture_content=8, density=50, exposure_time=24)
print(f"Predicted thermal resistivity: {result:.3f} m.K/W")  # Change inputs as needed
```

A comparison between measured and predicted thermal resistivity values is plotted in a graph and shown in Fig. 11; the error rarely exceeds 15% for both sand types.

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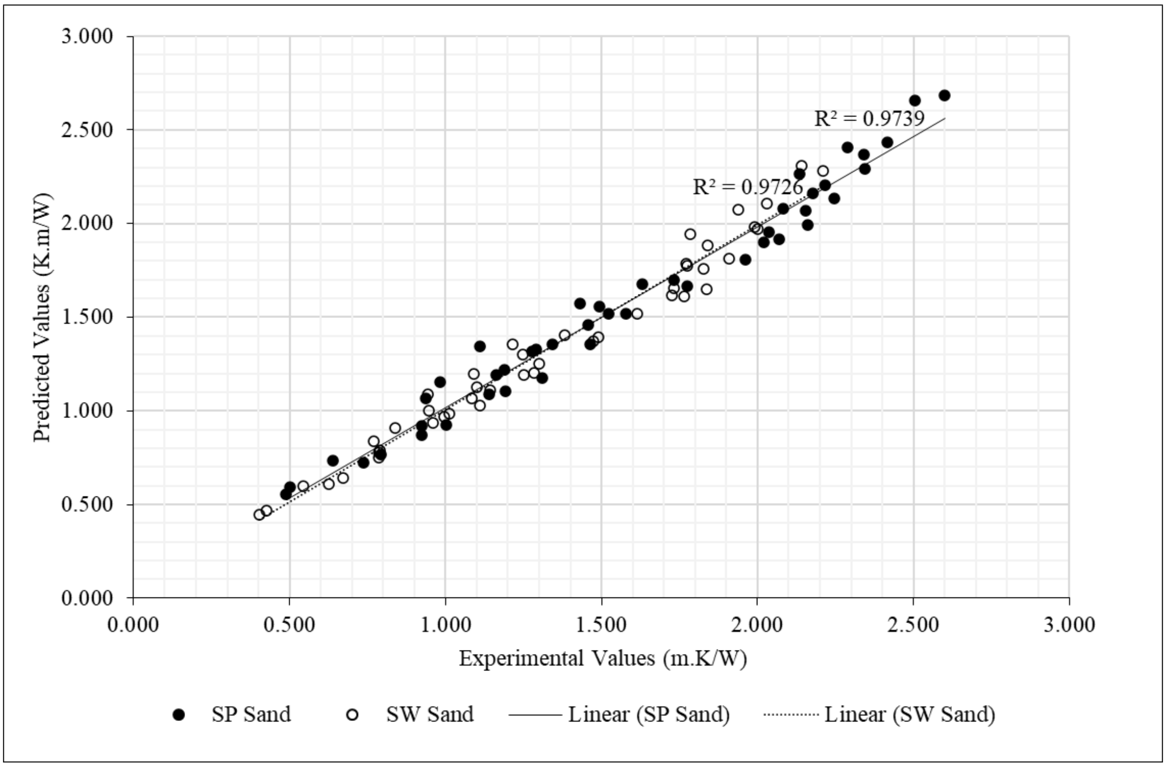

Fig. 11 Comparison of Experimental and Predicted Thermal Resistivity Values for SP and SW Sands Using Multilinear Regression Model

1. CONCLUSIONS

This comprehensive experimental investigation of thermal resistivity in sand backfills for buried transmission cables yields several significant findings that advance both scientific understanding and practical engineering applications:

1. *Influence of Soil Properties*

The thermal resistivity of sand is fundamentally governed by gradation characteristics, with well-graded (SW) sand consistently demonstrating 10-15% lower thermal resistivity compared to poorly graded (SP) sand across all tested conditions. This superiority stems from enhanced particle packing efficiency, which creates more effective heat transfer pathways through improved interparticle contact and reduced air-filled voids.

2. *Moisture Content Effects*

Moisture content emerges as the most critical parameter affecting thermal resistivity, with dramatic reductions observed as water content increases from 0% to 8%. For SP sand at 20% relative density, thermal resistivity decreases from 4.401 K.m/W (dry) to 0.640 K.m/W (8% moisture), representing an 85% reduction. This behaviour is attributed to the formation of continuous moisture films that facilitate thermal conduction between soil particles.

3. *Density Optimisation*

Increasing relative density from 20% to 80% consistently reduces thermal resistivity by 15-25% across sand types and all moisture conditions. This effect becomes more pronounced at lower moisture contents, where solid-phase conduction mechanisms dominate heat transfer processes.

4. *Atmospheric Exposure Impact*

Environmental exposure significantly alters thermal properties, with the most dramatic changes occurring in initially moist soils. High moisture specimens (8%) experience thermal resistivity increases of up to 158% within 24 hours due to evaporative moisture loss, while low moisture specimens (2%) show minimal sensitivity to exposure duration.

5. *Predictive Modelling Achievement*

The developed multilinear regression model successfully captures the complex interplay between sand type, moisture content, density, and exposure time, achieving excellent predictive accuracy ($R^2 = 0.97$) with mean errors below 6%. This model provides a practical tool for engineers to estimate thermal resistivity without extensive laboratory testing.

6. *Engineering Implications*

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These findings have direct applications for underground cable system design, suggesting that well-graded sand backfills with controlled moisture content and proper compaction can significantly enhance thermal performance. The sensitivity to atmospheric exposure emphasises the importance of moisture protection during installation and consideration of long-term environmental effects.

7. Future Research Directions

While this study provides a solid foundation, future investigations should explore the effects of different particle shapes and mineralogy, as well as long-term field performance under varying climatic conditions. Additionally, developing predictive models for other soil types would further enhance the practical utility of this research.

The results of this study provide valuable insights into thermal geotechnical engineering and practical guidance for optimising sand backfill selection and design in underground power cable installations, ultimately supporting more efficient and reliable electrical infrastructure systems.

Quantitative Assessment of Ampacity Enhancement

Quantification of Ampacity Gains to estimate the practical benefit of these findings, the potential increase in current carrying capacity (Ampacity, I) can be approximated using the inverse relationships defined in IEC 60287 and the Neher-McGrath method, where ($I \propto \frac{1}{\sqrt{\rho}}$). Comparing a conservative design scenario where the backfill dries to 2.5 K.m/W (ρ_{dry}) against the optimized moist condition of 0.6 K.m/W (ρ_{wet}) achieved in this study, the theoretical improvement factor is calculated as:

$$\text{Improvement Factor} \approx \sqrt{\frac{\rho_{dry}}{\rho_{wet}}} = \sqrt{\frac{2.5}{0.6}} \approx 2.04$$

While the total cable rating is also constrained by the thermal resistance of the cable insulation and duct bank, this reduction in the soil's thermal barrier effectively doubles the heat dissipation capacity of the surrounding medium. In practical engineering terms, this translates to a potential ampacity increase of approximately 30–50%, or allows for the selection of a smaller conductor cross-section for the same load, yielding significant project cost savings.

Research Limitations and Future Prospects

While this study provides a robust evaluation of thermal resistivity for specific sand gradations, certain limitations must be acknowledged to contextualize the findings for practical application.

First, the experiments were conducted under controlled laboratory conditions using standardized, homogeneous compaction methods. In actual field installations, non-uniform field compaction and spatial variability in soil density may lead to localized thermal hotspots that this uniform model does not fully predict.

Second, the scope of this investigation was limited to clean, granular sands (SP and SW). The behavior of soils with significant fines content (silt or clay) or differing mineralogical compositions was not assessed. The presence of fines could significantly alter capillary moisture retention and, consequently, the thermal bridging mechanism described herein.

Third, while the study examined short-term atmospheric drying, it did not account for long-term biogeochemical processes or complex environmental stressors, such as diurnal temperature cycles and seasonal wetting-drying hysteresis, which may affect the long-term evolution of the backfill's thermal properties.

Consequently, the multilinear regression model developed in this study is empirical and specific to the materials tested. The extrapolability of the model to other soil types or environmental conditions should be treated with caution. Future research should aim to bridge these gaps by conducting field-scale validation studies and investigating the combined effects of fines content and cyclic environmental loads on the thermal stability of cable backfills.

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Vijayakumar Anbalagan and Umanath Umaiyan. The first draft of the manuscript was written by Umanath Umaiyan, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

The datasets generated during and/or analysed during the current study are not publicly available due to the confidentiality of the company's policy but are available from the corresponding author at a reasonable request.