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Experimental study of thermal performance of the backfill material around underground power cable under steady and cyclic thermal loading

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Abstract

An experimental program is conducted to investigate the response of a dry soil heated by a cylindrical heater. The motivation for the work comes from its application to underground power cables which are employed for low, medium and in future for the high voltage electricity transportation and distribution. Due to the Joule heating, the power cables generate heat that has to be dissipated through the surrounding soil to prevent melting of the insulation and keep the cable below the safe operating temperature levels. Heat generation also causes the migration of moisture from the vicinity of the cable and allowing the formation of a dry out zone. The dry out zone due to loss of moisture becomes less thermal conductive and starts to heat up the power cable even faster. To prevent the damage in the cable the Ampacity or the current carrying capacity of the cable is reduced. Therefore, in this study, we modified the backfill material around the cable based on Fuller modification to achieve maximum density in the dry state (critical state). A large-scale experimental device is set up and tests were performed to observe the change in the thermal behavior of the backfill. A 5 days heating and cooling cycles of 12 hours are performed on the sand and modified backfill material and later allowed to relax for two days. The heat relaxation time for different heating conditions has been studied to quantify the nature of the backfill material for different loading scenarios.

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Keywords: Soil thermal conductivity; Modified backfill; Underground power cables; Large scale experiment; Soil physics.

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1. Introduction

With the shift of focus on renewable energy, new demands have been generated on the power transmission and distribution networks in Germany. While the solar energy can be produced often close to the consumption site, wind, geothermal and tidal energy productions are limited to a favorable site with abundance for production.

Most of the wind parks for offshore production are situated in the North Sea. However, the onshore production is concentrated in the central parts of Germany dictated by the strong wind sites. In contrast, the population centers of energy consumption are in the more densely populated and more industrialized south. The expansion of alternative energy production such as wind, geothermal and solar is driven by subsidies, but the same is not planned for the capacity expansion of the transmission networks. By 2020, at least 45% of net electricity production will be generated from renewable sources [1].

The German federal government has planned to move completely to renewable energies by 2050. The proportion of regenerative energy sources to gross electricity consumption by 2050 will rise to 80% [2]. The transport of the planned amounts of energy requires high-voltage power lines. Nationwide, about 3800 km of the new transportation network is required to adjust the power supply. This new network development plan will cost about 20 billion euros. The existing transmission networks operate at a voltage of 380 kV are by the high-tension overhead transmission lines. These overheads lines are routes are at least 60 m high and occupy an operating width of approximately 30 m. The lines follow uneven terrains are difficult to maintain due to track control systems, landscape and causing environmental damages such as infrasound, (humming) electro smog and bird strike (400-700 birds die per year per kilometer).

The underground power cable system is limited due to soil thermal conductivity due to drying up of the trenching material and the surrounding soil from the cables which endangers the melting of the XLPE insulation around the conductor due to Joule heating [3]. The thermal analysis of buried power cables is the crucial factor to compute the ampacity or the current carrying capacity. The International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE) standards [4-6] still follows the one-dimensional homogeneous analysis of Neher and McGrath [7] for the computation of the thermal resistance computation between the cable and the surroundings. The method was extended by Sellers and Black [8] to take into account the different thermal conductivity of the trenching material. Many different studies were performed by various researchers to computer mathematically [9,10] or numerically [11-13] the temperature fields around the cable. A very few experimental observations [14-16] were performed to study the behavior of these cables and the improvement in heat dissipation abilities.

The thermal conductivity of soil is strongly dependent on the moisture content and the porosity of the trenching material [17, 18]. Prevention of moisture migration is difficult to achieve due to continuous heating of the operating cables thus leading to a permanent loss of moisture in the backfill material rendering the soil partial or completely dry and allowing the formation of ‘hot spots’ around the cables [19]. A general practice for these underground power cable is to fill the trench with sandy soil [20]. However, the dried sand has thermal conductivity value of only one fourth to one sixth that of the wet sand and the moisture migration is inevitable. The other possibility for thermal conductivity enhancement is the modification of gradation or reducing the pore space and thus increasing the quality and quantity of the thermal conduction channels [21,22].

In this study, we modify the porosity of the sand with bentonite and developed a new filler material capable of achieving high conduction value at a very nominal price in the dry state as backfill material. A large-scale experimental device is set up and two different trenching materials, namely the sand (same as the surrounding material) and the developed material are tested with cyclic loading and the temperature recording was made at the designated location. The explanation of the experimental setup is given in section 4.

2. Materials

The sand is collected from a nearby region in Kiel, Germany. The mineral composition of the sand was determined semi-quantitatively by X-ray diffraction (XRD) analysis. The sand has over 90% quartz content and other minerals in trace quantity, to be 2.64. The grain size distribution of the sand is plotted in Figure 2. At the minimum and maximum namely feldspar. (Fig. 1) The grain density of the sand was found to be 2.64. The grain size distribution of the sand is plotted in Figure 2. At the minimum and maximum compaction, the void ratio is between 0.53 and 0.8. As the previous studies suggest the thermal conductivity is inversely proportional to the void ratio. A void ratio of 0.5 it tried to attend with hammer and vibration compaction, but the minimum value of 0.53 was achieved. Therefore, modification of gradation was applied following the Fuller scheme to achieve a minimum void ratio.

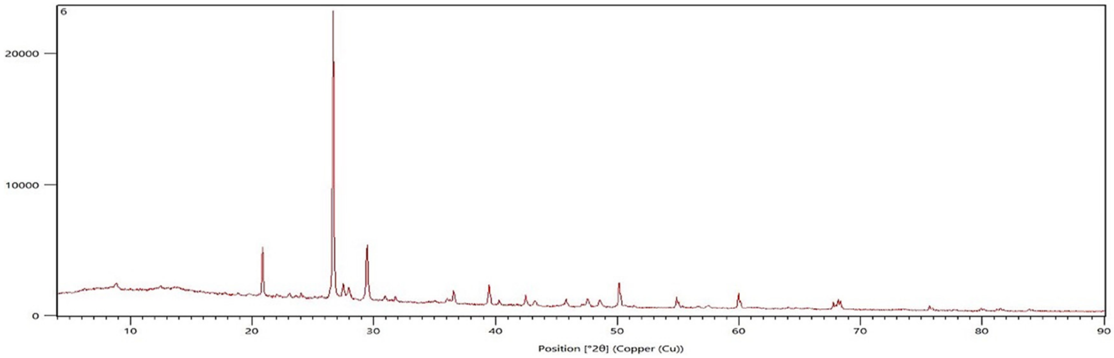

Fig. 1. X-ray diffraction (XRD) of the sand showing the dominant signature of quartz mineral.

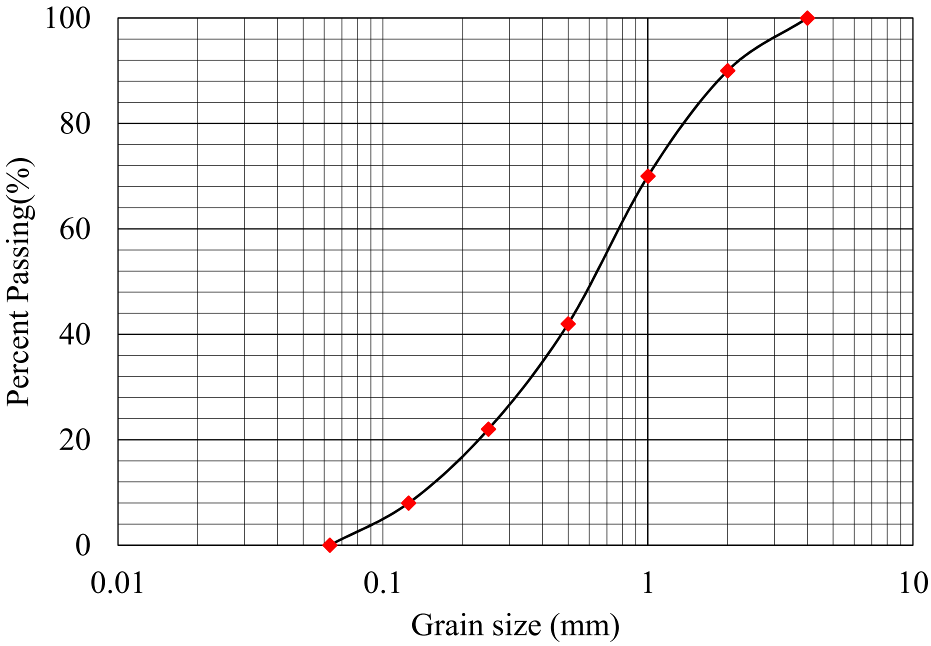

Fig. 2. Grain size distribution of sand. The sand is a uniformly distributed medium sand.

The 2mm Fuller gradation curve has been implemented by removing all the grains lower than 125 microns with an equivalent percentage of bentonite. A microscopic study with scanning electron microscopy (SEM) is performed to observe the changes in the developed mixture. (Fig 3) For the dry granular media, the quality and quantity of contacts improve and enhance the intergranular and intra-granular heat conduction capacity by forming and strengthening the thermal bridges and by filling and smoothening the intra-granular defects, respectively.

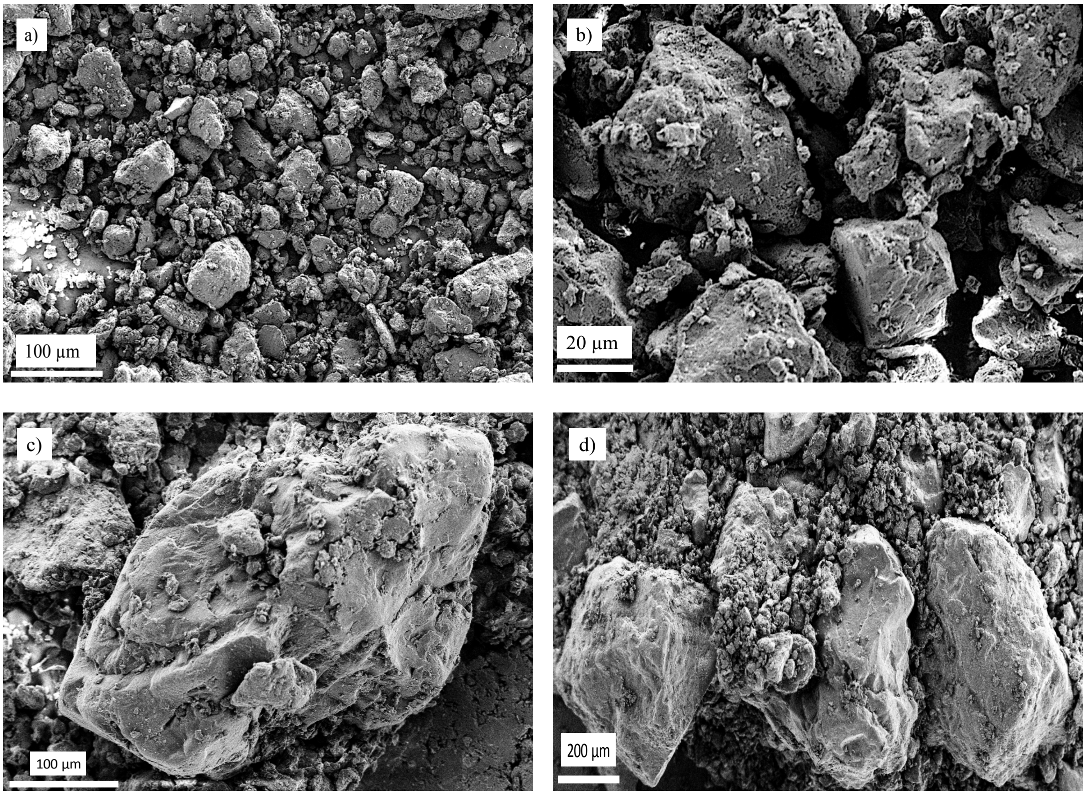

Fig. 3. SEM pictures of the filler Bentonite used to achieve the density correction. a) Bentonite of sizes between 0-125 micron. b) A zoomed picture of bentonite fillers showing the texture and shape of the filler. c) A grain of sand with surface imperfections and the filler bentonite smoothening and filling the intragranular defects. d) enhancement of the existing granular bridges among the sand grains and formation of extra bridges due to filler.

In this study, the fuller curve of 4mm and 2mm is considered owing to the maximum particle size of sand in the mixture. The Fuller curve gradation of 4mm and 2mm are also shown in Figure 9. The fines in this study are sodium bentonite (particle size lower than 125µm), with 18% and 25% by volume for 4mm Fuller curve gradation (4mmF) and 2mm Fuller curve gradation (2mmF) for all sands. The added filler acts as inter-granular bridges to improve the quality and quantity of contacts by increasing number of contacts due to larger surface area as thermal conduction in dry soils is mainly attributed to inter-particle contacts [23].

3. Measurement of Soil Thermal Conductivity

A cylindrical mould of 5 cm diameter and 14 cm in height is fabricated and the material is compacted at different densities corresponding to targeted porosity values. However, a variation of 0.2% in porosity value is tolerated. Three measurements were performed for each prepared sample and three different samples were prepared. The tested materials are oven dried at 105 ^{o}C for 24 hours and then left in the desiccator for cooling. The measurements were performed at room temperature of 20±2 ^{o}C.

The thermal conductivity measurements were performed with Decagon KD2 Pro device. This device follows the ASTM D5334-08 [24] and IEEE standards [25]. The thermal probe (TR-1) of 10 cm in length and 0.24 cm in diameter is used for all the samples. The measurement device follows the transient line source theory and therefore a sufficient needle length to diameter ratio is taken into account for fabrication and the conditions for an infinitely long and infinitely thin heating source are met.

The results of the measured value for the sand and the modified backfill material is given in the figure. A negative linear proportionality is observed for the sand in the porosity range of 0.32 to 0.45. This observation confirms the correlation of quality and quantity of grains in contact with the change in the effective thermal conductivity value. However, the trend becomes non-linear for the modified material. The observation reflects that initially at higher porosity the fillers are filling the pores help in forming extra conduction channel. But as soon as the critical porosity value is achieved the non-linear trend disappear and a linear rise as in the case of sand is observed. Formation of intergranular bridges is shown with SEM in figure 3d. The observation confirms the hypothesis. (See Fig. 4)

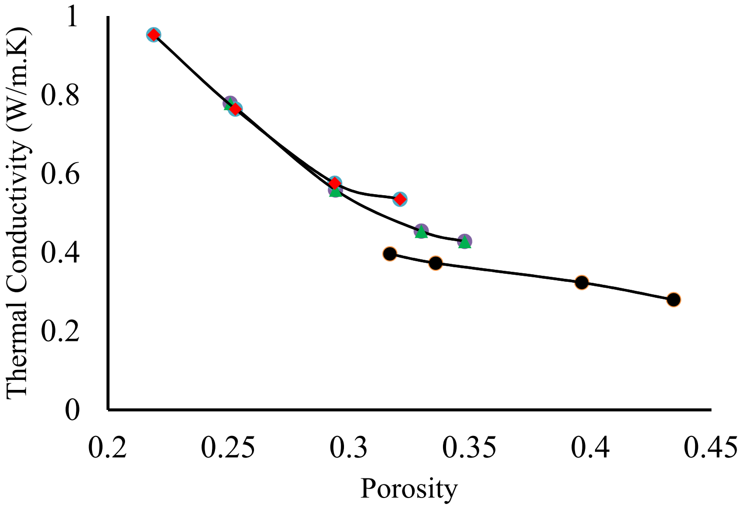

Fig. 4. Change in the Effective thermal conductivity of the sand and the modified backfill material with the change in porosity value.

4. Experimental Setup

The experimental setup was designed for recording temperature and moisture content around the heated cylinder which simulated as the underground power cable. A container 1800 mm long, 1000 mm wide and 1200 mm high were fabricated with plexiglass on its four faces for clear visual inspection as shown in Fig.5. The complete schematic diagram for the container along with the positions of the thermocouples is shown in Fig. 5(b). The box was cover from the top by a thin Aluminum sheet which was covered under a layer of sand to avoid escape of heat from the container. Care was taken while filling the sand and modified material into the container so that no thermocouple wires are broken and they remain intact at their respective position.

The heater rod (cylinder) employed here, was firmly secured between two vertical stands as shown in Fig. 6(a). It is primarily a steel tube which is 800 mm long having an external diameter of 50 mm and devising an electrical heater inside it, tightly secured between two nylon supports each 50mm wide. A schematic diagram of the heated cylinder is shown in Fig. 6 (b). The heated cylinder was then covered with aluminum sheets for uniform heating. The heater was laid horizontally along the width of the container i.e. parallel to the 1000 mm width side. National Instruments thermocouples and moisture sensors were used for the data acquisitions which were placed at pre-decided locations starting from the heater surface as shown in Fig. 5 (a, b) in both the horizontal and vertical plane.

The distances of the thermocouples shown in the figure are with respect to the surface of the heated cylinder (see Table 1). In total, there were thirty-one thermocouples and eight moisture sensors to record temperatures and soil moisture content. Out of the thirty-one thermocouples two were placed outside the container, one on the top of the container in the vertical plane of the heated cylinder and one in line with the heated cylinder in the horizontal plane to record the ambient temperature. While modified material was studied along with sand the trench size for modified material used was 1000 mm long, 300 mm wide and 500 mm deep.

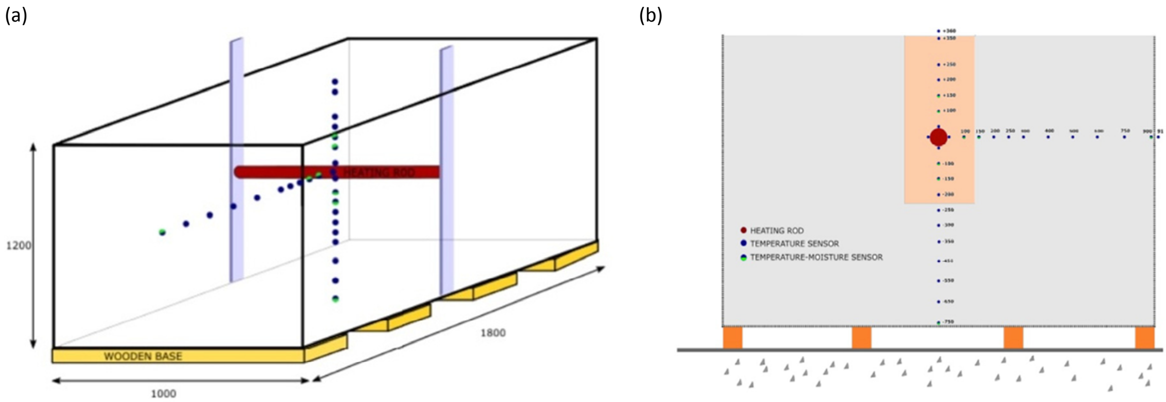

Fig. 5. (a) Position of Thermocouples in 3D (b) respective distance of thermocouples

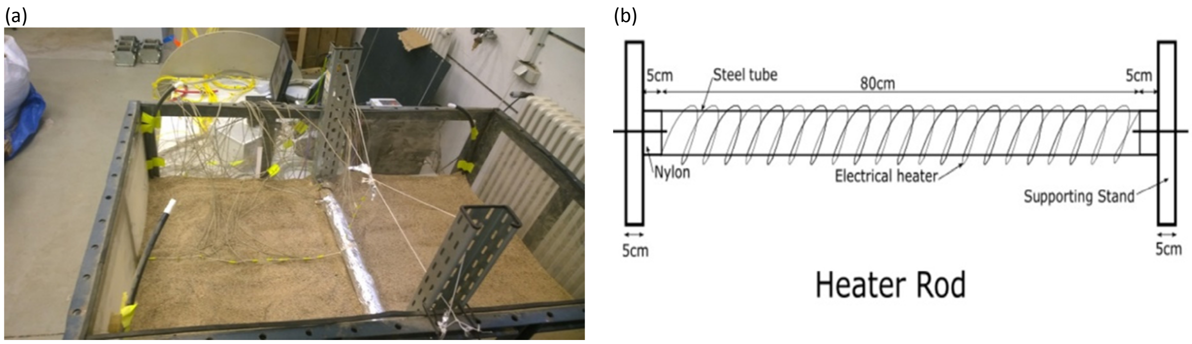

Fig. 6. (a) Heater Rod, (b) Schematic Diagram of the Heater Rod

5. Results and Discussions

The experiment was carried out in two phases; firstly, with only sand in the container and secondly, with both sand and modified material. Symmetric study for a period of 12 hrs. (i.e. 12 hrs. of heating & 12 hrs. of cooling) was common in both the phases whereas with the modified material, unsymmetrical study was also carried out for different heating and cooling periods which are discussed in the ensuing section. The motive of studying the thermal behavior of sand alone was to check how does the sand behaves around the heated cylinder and also to compare the effectiveness of the developed modified material. The entire results are expressed in three parts: Sand, Modified Material, Comparisons and Relaxation Time.

5.1. Sand as the backfill

A symmetric study was carried out with only sand in the container. The cylinder was heated for a duration of 12 hrs. and then allowed to cool for another 12 hrs. During heating, the temperature was kept at 90°C. The study was carried out for 6 cycles of symmetric heating i.e. for a total duration of 144 hrs. Fig. 7 (a, b, c) shows variation of temperature for different thermocouples placed above, below and in the plane of heated cylinder at their respective locations. As expected the thermocouples close to the heated cylinder recorded higher temperature as compared to the others. Further, Fig. 7 (d, e, f) shows much clearer understanding of temperature at a distance of 50mm &

100mm from the heated cylinder's surface. Also, it can be noted that for same distance temperatures were higher in the thermocouples placed above the heated cylinder as compared to ones below and in the horizontal plane with lowest in the ones below the heated cylinder, the same was also reported by Moya Et al. [10]

5.2. Modified Material as the backfill

The symmetrical study of 12 hrs. was conducted for a period of five cycles and a total duration of 120 hrs. It can be evidently observed from Fig. 8 (a, b, c) that as the distance increases i.e. if we move far with respect to the heated cylinder the temperature decreases and exhibiting at the same time that the soil is more responsive near the heated cylinder. In our study we are measuring soil response as the time taken to heat and cool for their respected durations of heating and cooling thus, if we take the case of thermocouple A_7 (see Fig. 8 (a, d)) and A_{27} (see Fig. 8 (a)) we can clearly see that soil is more responsive near thermocouple A_7 taking closely 12hrs. to heat and then again 12hrs. to cool but if we observe thermocouple A_{27} it took it nearly 19 hrs. to heat and then it remained constant within a range of ±3°C showing comparatively unresponsive condition and increased time lag. Initially there was a time lag of 7 hrs. in A_{27} as compared with A_7 which reduced to 2 hrs. by the end of the fifth cycle due to storage of energy in the system.

As the system keeps running energy is stored in the system making it impractical for use when it reaches a threshold value unless the system is shut down and allowed to cool. Symmetrical heating pattern could be observed in systems such as solar energy farms where energy is harnessed and transported during the day hours. A similar symmetric study of 1 hr. was also conducted where the test was running for 8 hrs. i.e. for a period of four cycles shown in Fig. 8 (a, b, c).If we examine Fig. 8 (d, e, f) we can see that it took one fourth of an hour to heat the thermocouples on the surface of the heated cylinder where the temperature in them remain constant for a total duration of one hour and followed uniform cooling pattern every cycle however ones at 50mm distance and others showed the same pattern as in symmetric 12hrs. study.

5.3. Comparisons

Comparisons have been made for a symmetric study of 12 hrs. between the modified material and sand. Fig. 9 clearly shows higher temperature in modified material as compared to sand which validates the higher thermal conductivity of the modified material, thus it can also be clearly understood that it would be easier for heat to escape the modified material as compared to sand with relatively less or no heat spots being created around the power cables (or used heated cylinder)

Table 1. Distance and Position of Thermocouples.

Position of Thermocouples	Name and Respective Distances (in mm from center of heater rod)
Horizontal Direction	A24 (50), A10 (50), A18 (100), A21 (150), A17 (200), A5 (250), A16 (300), A6 (400), A28(500), A22 (600), A23 (750), A13 (900), A_0 (910)
Above Heater	A30 (50), A7 (100), A11 (150), A14 (200), A26 (250), A9 (300), A27 (350), A8(360)
Below Heater	A31 (50), A20 (100), A4 (150), A2 (200), A1 (250), A3 (300), A19 (350), A15(450), A12 (550), A25 (650)

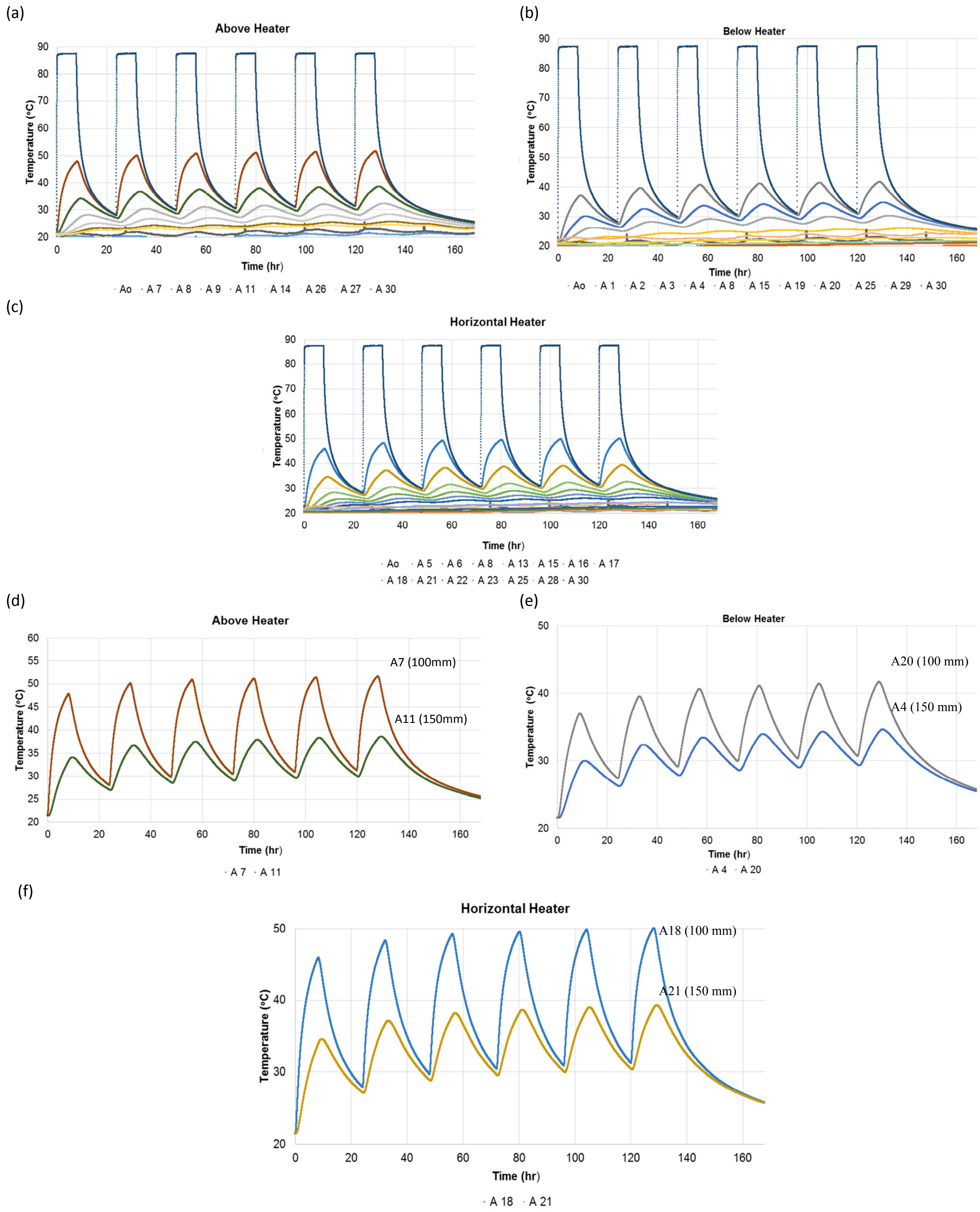

Fig. 7. For Sand as backfill: (a) Temperatures recorded by thermocouples above the heater, (b) Temperatures recorded by thermocouples below the heater, (c) Temperatures recorded by thermocouples in the horizontal direction, (d) Comparison of temperature in thermocouple A7 and A11, (e) Comparison of temperature in thermocouple A20 and A4, (f) Comparison of temperature in thermocouple A18 and A21

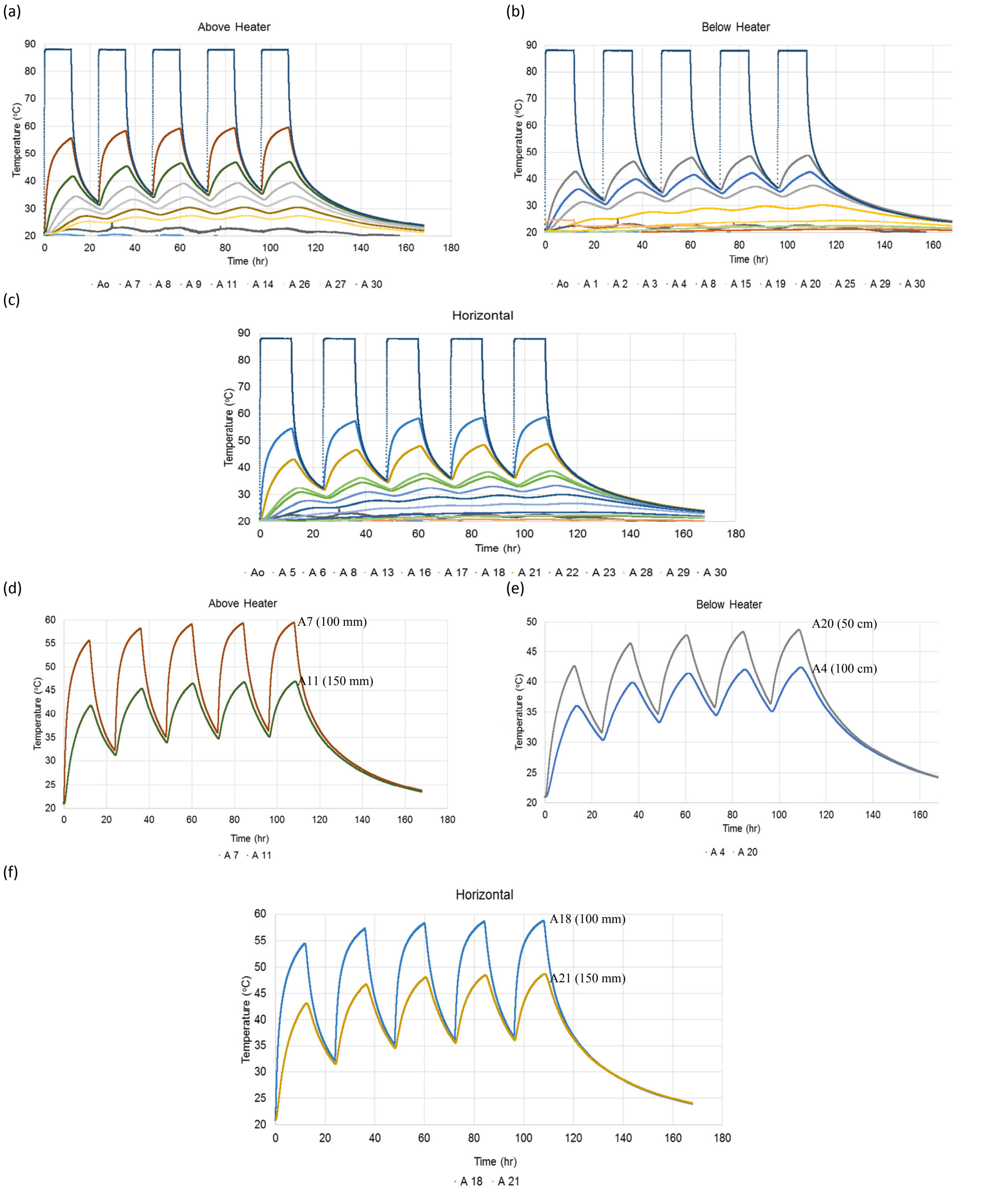

Fig. 8. For Modified Material as Backfill: (a) Temperatures recorded by thermocouples above the heater, (b) Temperatures recorded by thermocouples below the heater, (c) Temperatures recorded by thermocouples in the horizontal direction, (d) Comparison of temperature in thermocouple A7 and A11, (e) Comparison of temperature in thermocouple A20 and A4, (f) Comparison of temperature in thermocouple A18 and A21

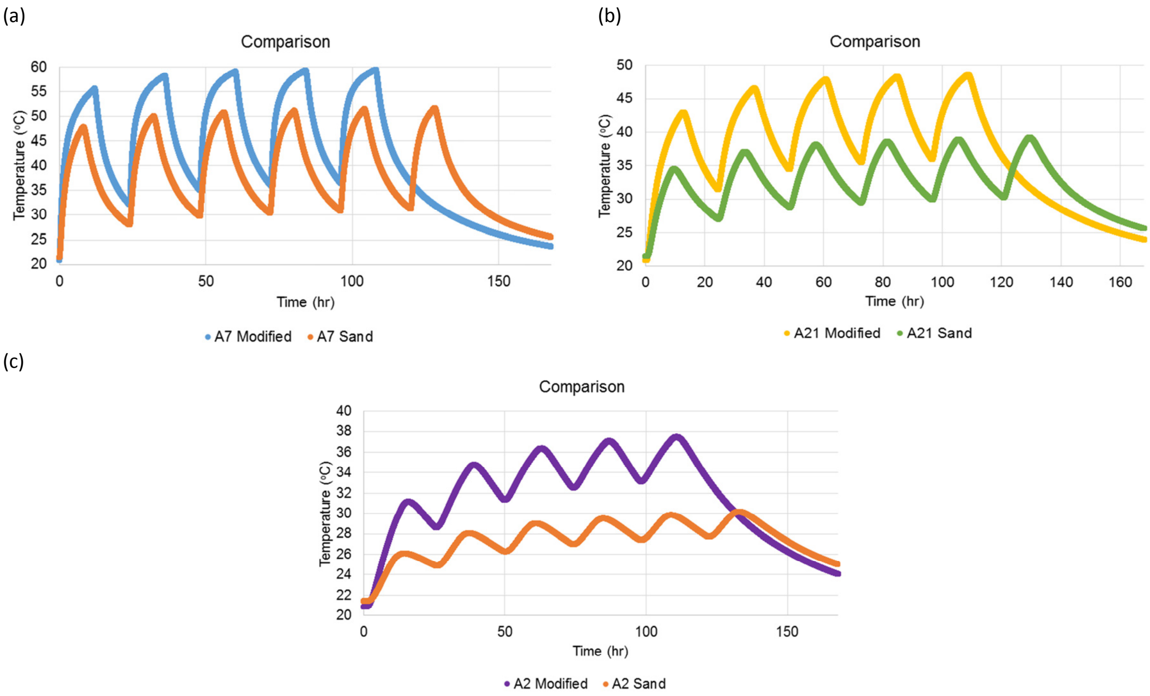

Fig. 9. (a) Comparison between Sand and Modified material for thermocouple A7, (b) Comparison between Sand and Modified material for thermocouple A21, Comparison between Sand and Modified material for thermocouple A2

6. Conclusions

In this study, a large-scale experiment is setup to study the thermal behavior of the underground power cable surrounded by dry backfill material. The drying of the cable resulting due to Joule's heating of the conductor which can also cause the insulation to melt if not dealt properly. The excess heat must be dissipated to the surrounding soil. Therefore, a box with electric heating of cylindrical shape is fabricated and temperature at predefined location at the middle vertical plain perpendicular to the heater and middle horizontal plain. A trench scenario is created and a bentonite based modified material is developed and filled in the trench around the cable and the tests with different thermal loads were performed. The following conclusions are drawn from the study:

- The modified material improved the effective thermal conductivity due to improvement in quality and quantity of contacts thus enhancing the conduction channels.
- The developed material enhances the heat transport capabilities around the heater however the energy of the system increases with each heating cycle.
- The far field temperature sensors are less affected by the rising heater temperature but the effect is felt at each sensor immediately.

Acknowledgement

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