Climate resilience and energy harvesting of thermo-active roads

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Abstract. The climate is changing rapidly, altering the long-term environmental loading parameters of roads. Increased frequency and severity of extreme weather events cause serious road damage and transport disruption, including melting roads in heatwaves and potholes due to freeze-thaw cycles, with highway repair and maintenance costing England alone £1.4 billion in 2021/2022. The recent established UK projects SaFEGround, Digital Roads, and an RAEng Research Fellowship will synergise ideas and methods to develop low-carbon and resilient roads. In particular, the RAEng Research Fellowship involves deploying an innovative shallow geothermal energy system (SGES) for subgrade heat storage/extraction and pavement temperature regulation. Such research is at the forefront of Transport and Energy Geotechnics. Very little research has been conducted on the pavement-pipe-subgrade SGES and factors affecting their performances, especially in the field of civil engineering (e.g. thermal properties enhancement of subgrade materials, pavement/pipe/subgrade interaction, complex thermo-mechanical behaviour under extreme climates). This paper provides an overview of the systematic research approach that fully characterises thermally improved road materials via physical modelling, finite element numerical analysis, field trials and LCA, with some preliminary results analysed. The proposed thermo-active road technology would be applicable to a wide range of transport projects in many regions to reduce climate-related road maintenance costs and carbon emissions.

Keywords: Climate Resilience, Thermo-active, Pavement.

1 Introduction

The swift pace of climate change is significantly altering the long-term environmental stressors impacting the UK's 262,300 miles of roads. The escalating severity and frequency of extreme temperature fluctuations result in substantial pavement damage. Numerous climate change-related effects on roads have been identified, including but not limited to (1) rutting and curling due to high temperatures; (2) cracking at low temperatures; (3) excessive deformation caused by freeze-thaw cycles; and (4) increased subsurface expansion and contraction if pavements rest on expansive clays and unstable ground [1-3]. The cost of road repair and maintenance in the UK stood at £1.4 billion in 2020/21, underscoring the critical importance of improving road resilience to climate change.

Thermal pavements, which mitigate the effects of snowy and icy road conditions, have been the subject of research since the early 1950s. Chapman developed a formula in 1956 to calculate the heat output required by snow melting systems [4], a formula that is still employed in contemporary studies [5, 6]. Most road heating systems are designed as electric heating systems [7]. However, the repercussions of climate change have necessitated the exploration of alternative heating methods, particularly those harnessing geothermal energy. Shallow geothermal energy systems (SGESs) are regarded as one of the most efficient and environmentally friendly solutions for heating and cooling [8]. A summary of recent analyses on ground heat exchangers (GHEs), specifically on energy piles, can be found in [9].

A significant advantage of a non-electrical, hydronic heating system is the ability for water to circulate throughout the year, enabling pavements to be heated and cooled using the same water circuit. This method is applied in the Swiss SERSO project [10], for example. The thermal energy generated by solar radiation in Europe is presumed to far exceed the thermal energy required for de-icing and snow melting. Therefore, the heat extracted by such a system in the summer could be effectively utilized for heating in the winter. A similar trial of thermal pavement systems, termed 'Inter-seasonal Heat Transfer', was conducted by UK National Highways in 2006/07, with the aim of storing heat in shallow insulated ground for subsequent reuse [11]. Despite investigations into geothermal pavements from a heat transfer perspective, these studies were based on experimental data dealing with short-term performance [12]. Consequently, there is a pressing need for long-term monitoring and examination of the thermo-mechanical performance of pavement-GHE-subgrade systems.

Researchers are increasingly turning to numerical solutions to gain a deeper understanding of the heat transfer process, due to their wider applicability and fewer constraints in exploring geometry and configuration than laboratory or field-scale experiments allow [13-15]. However, there is a dearth of research on horizontal SGESs installed in improved subgrade soils and their modelling. Soil thermal properties have the most significant impact on subsurface heat transfer, but most developed numerical models assume constant soil properties throughout the modelling process for the sake of simplification and computational efficiency [16]. In a recent study, Han et al. (2017) developed a 3D finite-element model to evaluate the thermal performance of various horizontal SGES configurations and to investigate the importance of using local geological data (measured ground temperatures and soil properties) as design inputs to enhance modelling accuracy [14].

There are several challenges associated with geothermal heating and cooling systems for roads. Efficient heat transfer and storage in the road-pipework systems are dependent on the high thermal conductivity and specific heat capacity of the road materials. Minimal research has been conducted, either experimentally or theoretically, on the long-term performance and determination of factors related to civil engineering materials (e.g. the effect of thermophysical properties of road materials, the road/pipe interface, and the depth of the embedded pipe). Hence, it is both innovative and timely to conduct research into the performance of thermo-active roads and attempt to enhance this through material and design optimisation.

2 RAEng Fellowship Project

Some recent established UK projects, including SaFEGround, Digital Roads, and an RAEng Research Fellowship, are synergising ideas and methods to develop low-carbon and resilient roads. In particular, the aim of the RAEng Research Fellowship is to develop climate-resilient and heat-harvesting roads by deploying an SGES for subgrade heat storage/extraction and pavement temperature regulation to reduce climate-related road maintenance costs and carbon emissions. The objectives are:

1. Develop novel microencapsulated phase change material (PCM) with graphite-based shells for enhanced thermal conductivity and specific heat capacity, and characterise the subgrade soils improved with low-carbon geopolymer grout incorporating the developed microcapsules.
2. Build a model thermo-active road coupled with a GHE system in large soil chambers to evaluate its thermal performance and resilience in extreme climatic conditions.
3. Develop a state-of-the-art finite element numerical model for the coupled thermo-hydro-mechanical processes and understand the response of the roads to long-term environmental loads by implementing meteorological data of various climatic regions in the UK.
4. Quantify the impacts of the developed novel subgrade materials and operation methods on temperature regulation and heat harvesting performance with the field trial of a fully instrumented thermo-active road segment.
5. Assess the life-cycle economic and environmental impacts of thermo-active roads and assess their contribution to delivering UK National Highways' net-zero plan for road construction, maintenance and operations by 2040.

The proposed innovative thermo-active roads constitute a promising application of horizontal GHE installed in thermally improved subgrade for which little available information exists and form the focus of the proposed Fellowship. A schematic representation of the proposed road and its components can be seen in Figure 1. GHE pipes are implemented in the subgrade incorporating microcapsules to efficiently exchange heat and the pipes are connected to a heat pump to provide heating/cooling for the pavement to adapt to changing climates, reducing climate-related road maintenance costs and carbon emissions. Furthermore, thermo-active roads can easily be combined with other renewable sources, such as solar, to achieve heat harvesting and storage. Conducting experimental investigations and developing numerical models are useful for providing insights into thermo-mechanical behaviour as well as evaluating the performance of the technology. A better understanding of these can lead to the speedier adoption of novel thermo-active roads and net-zero transformation of transport infrastructure. It is, therefore, novel and timely to conduct such research. The development of climate-resilient and heat-harvesting roads will represent a step-change in UK transport infrastructure and is at the heart of the National Highways' vision for the Strategic Road Network.

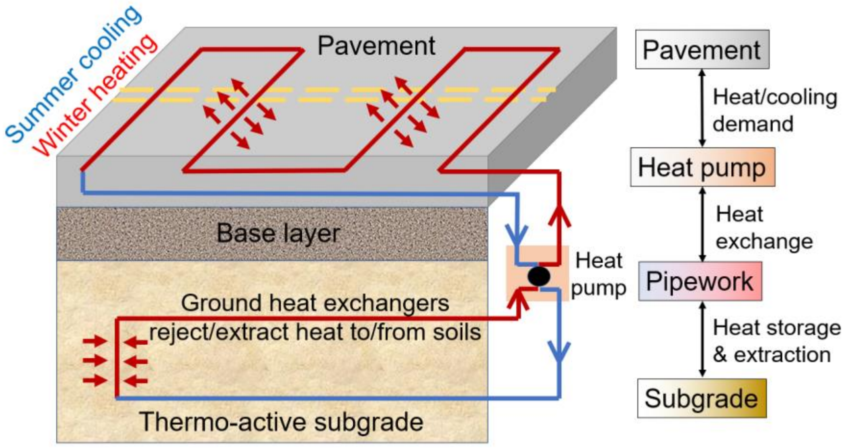
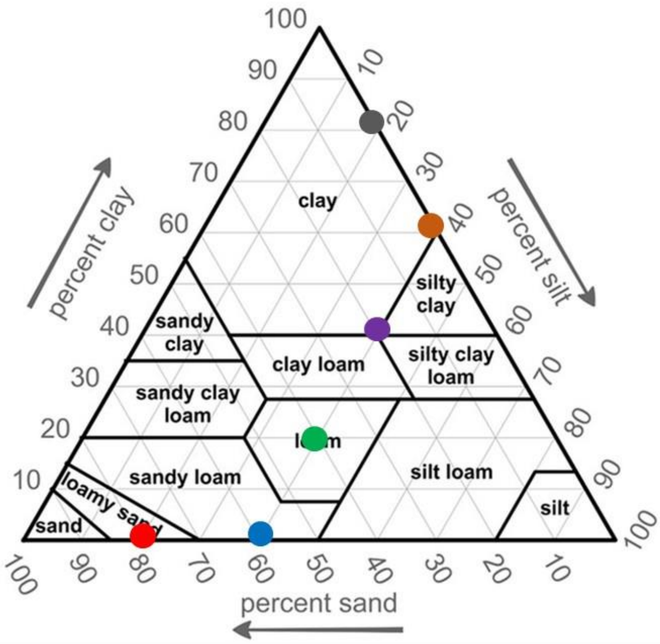


Fig. 1. A figure caption is always placed below the illustration. Short captions are centered, while long ones are justified. The macro button chooses the correct format automatically.

3 Preliminary Results

The present preliminary work aims to develop conductive cement grout for subgrade thermal conductivity enhancement. By changing the component share of sand, silt and clay, six types of subgrade soils were produced to cover a wide range of soils encountered in geotechnical projects. These six types of soils are presented in ternary combinations (sand-silt-clay) in Figure 2.

After selecting the optimal conductive filler type and content (10% graphite flakes) and choosing CEM VI as the binder due to its markedly lower carbon emissions, the conductive grout was mixed with a wide range of soils and examines the thermal conductivity enhancement. The aim is to use as little cement as possible to achieve a satisfactory increase in thermal conductivity. Therefore, this work started by mixing the grout with 12 soils at a soil-to-cement ratio of 6:1.



Soil ID	Type	Sand % by weight	Silt % by weight	Clay % by weight	Dry soil void ratio (max/min)	Dry soil bulk density (max/min) g/cm³
A	Silty Sand	80	20	0	0.88 / 0.45	1.83 / 1.41
B	Very Silty Sand	60	40	0	0.91 / 0.50	1.77 / 1.39
C	Sandy Silt	40	40	20	1.45 / 0.96	1.32 / 1.06
D	Clayey Silt	20	40	40	2.05 / 1.33	1.12 / 0.85
E	Very Silty Clay	0	40	60	2.54 / 1.53	1.03 / 0.74
F	Silty Clay	0	20	80	3.02 / 1.94	0.88 / 0.65

Fig. 2. Properties of the six types of soils in ternary combinations (sand-silt-clay).

Figure 3 compares the thermal conductivity (λ) values of dry and half-saturated native soils and the soils mixed with two grouts with different W/C ratios. For dry soils the conductive grout markedly increases their thermal conductivity, and the grout with W/C=2.0 (VI_2.0_10%) achieved higher λ than that with W/C=1.0 (VI_1.0_10%). Take the dry Soil B for example, a typical alluvial sand widely encountered in low-lying floodplains of river valleys: mixing the soil with VI_2.0_10% Gr grout at a soil-to-grout ratio of 6:1 increases the λ from 0.19 to 2.62 W/m·K - a remarkable 14-fold increase. Also, for the dry Soil E, a representative silty clay occurring across the south of England, the λ significantly increases 13-fold from 0.12 to 1.60 W/m·K. This indicates that the mixing of dry native soils with conductive grout is a very effective way to increase the λ by over an order of magnitude. The grouts with W/C=2.0 outperform W/C=1.0, because at such a high soil-to-grout ratio of 6:1, higher W/C means better flowability of the grout and consequently, more uniform mixing with the soil. In contrast, the λ of wet soils (Sr=50%) failed to rise notably regardless of the W/C ratio of the conductive grout: slight increases by 12% and 32% for wet Soil B and E were seen when mixed with VI_1.0_10% Gr grout. Unlike in the case of dry soils, the grouts with W/C=1.0 achieved higher λ for wet soils, indicating that the formation of more solid phase in the matrix is key to the enhancement of heat conduction in already high-water-content soils. The limited increase in wet soil λ means that it might be unnecessary to mix or inject conductive grouts into native soils with a Sr > 50% for ground thermal improvement - the λ of wet native soils is probably high enough for geothermal applications and the marginal increase might not be cost-effective.

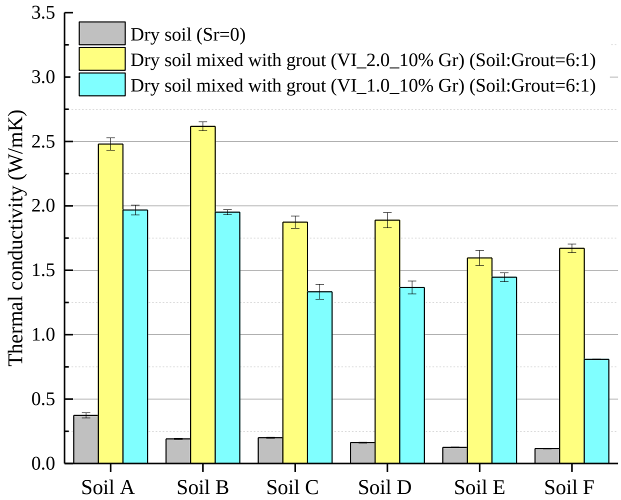


Figure 3. Thermal conductivity of dry soils mixed with conductive grout

Representative dry sandy and clayey soils, after mixed with the graphite-containing grout at a soil-to-grout ratio of 6:1, were analysed under SEM-EDX. Sand particles and graphite flakes were effectively encapsulated by the cementitious binders, exhibiting a uniform dispersion throughout the sand-cement composite (Figure 4 a&c). Certain flakes were observed to have come into contact with the sand surface, potentially reducing the interfacial thermal resistance. Similar results were obtained for clayey soils, where graphite flakes were firmly embedded in the matrix and contribute to heat conduction (Figure 4 b&d). Graphite flakes observed in the soil-cement systems were mostly unfolded and wrapped by the binder, indicating the thin layer structure of the flakes were not deformed and that no nearby macro-pores were produced because of the addition of graphite.

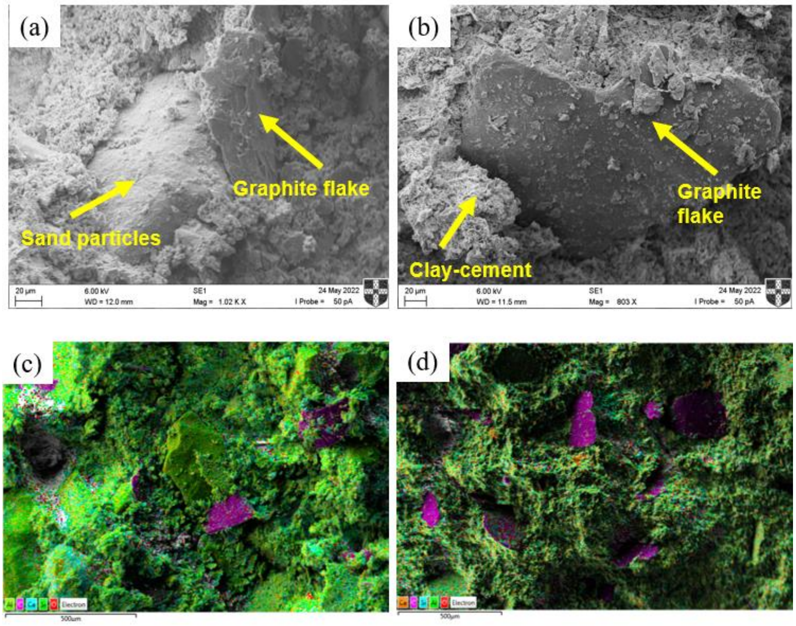


Figure 4. Graphite flakes were bonded within cement binders in sandy (a & c) and clayey (b & d) soils.

4 Conclusions

In conclusion, this paper highlights the pressing need for improved road resilience in the face of climate change, which is causing increasing damage to the UK's extensive road network. The potential of thermal pavements is discussed, which have been researched since the 1950s, and geothermal energy systems as promising methods to mitigate the effects of extreme weather conditions on roads.

There is a lack of research concerning the long-term performance of these systems, particularly regarding the modelling of horizontal SGESs installed in improved subgrade soils. The RAEng Research Fellowship project is then introduced, involving the development of novel materials and methods, experimental evaluation of thermal performance, numerical modelling of thermo-hydro-mechanical processes, and assessment of life-cycle economic and environmental impacts.

The preliminary results of the project indicate that the development of conductive cement grout for subgrade thermal conductivity enhancement is promising. The grout was mixed with a wide range of soils, and it was found that the thermal conductivity of the soils could be significantly increased.

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