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Title of Paper: Practical Application of Graphene Enhanced Concrete

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PRACTICAL APPLICATION OF GRAPHENE ENHANCED CONCRETE

ABSTRACT:

Incorporation of graphene nano-particles in concrete can improve mechanical properties and as a result has received growing attention in the research community. Despite the promise revealed in laboratory trials, there remain significant obstacles to widespread adoption of graphene in concrete at a construction level scale. This briefing paper gives an overview of the key outcomes from a recent experimental campaign and accompanying field trials where pioneering use of graphene enhanced concrete (GEC) has been successfully deployed at scale.

Keywords: Concrete technology & manufacture, Microstructure, Strength & testing of materials, Sustainability

INTRODUCTION:

In the drive towards more sustainable concretes, the use of nano-particles as a means of enhancing concrete's properties has been explored in recent decades. Most recently, the emergence of graphene and its potential use in concrete has gained attention in the research community. Existing experimental work has shown that at laboratory scale, addition of small amounts of graphene in various forms can result in significant enhancements in compression and tension strength, thus pointing towards a potential reduction in the cement contents needed to achieve the required design strengths in practice. Similarly, the piezo electric properties of some graphene products can be used to develop self-sensing or smart concrete structures (Papanikolaou et al, 2019).

Graphene is essentially a 2D sheet material which is formed by a single layer of carbon atoms approx. 0.335nm thick, these are arranged in a characteristic hexagonal lattice formation. Graphene sheets have been shown to exhibit a tensile strength of 130 GPa and a Young's modulus of 1.1 TPa, (Lee et al 2008). Various graphene nano-products have been researched to date, these include graphene nano platelets (GNP) which comprise between 1 and 100 graphene sheets and a thickness less than 100 nm. The most commonly researched graphene product in cementitious materials is that of graphene oxide (G0), this exhibits a similar tensile strength to pristine graphene however the Young's modulus is reduced to 23-42 GPa (Balaji & Swathika 2022).

Whilst experimental results underline the potential of graphene enhanced concrete, significant hurdles exist in terms of adoption in full scale projects. Crucially, the means of particle dispersion and the associated uniformity of dispersion are key to ensuring consistent and reliable GEC properties, see Figure 1. Most commonly, graphene nano-particles are suspended in solution which is then added to the wet concrete mixture. Uniform dispersal of pristine graphene in water is problematic due to the Van der Waals forces and the hydrophobic nature of the material. In the case of GO, the problem of dispersion in water is reduced due to the presence of hydrophilic function groups, however the chemistry of GO is such that piezo electric behaviour and hence smart capabilities may be inhibited, (Long et al, 2018).

MECHANICAL PROPERTIES OF GEC:

Graphene nano-particles influence the structure of the cement matrix in a number of ways that can lead to enhancement in mechanical properties. During the hydration phase, the relatively large surface area of graphene allows for an enhanced nucleation effect which in turn encourages cement hydration and the production of calcium silicate hydrated gel and ultimately leads to improved compaction of the cement particles. Typically cement contains pores at both the nano ($x10^{-9}$m) and the micro ($x10^{-6}$m) scale, any pores that would hitherto be present within the matrix are either filled or reduced in size by the graphene particles, see Figure 2. Lastly, micro cracking in the cement matrix can be either prevented or constrained by the bridging effect generated by graphene.

Existing experimental work on addition of graphene to cementitious materials has reported a wide variation in enhancement of mechanical properties. Tests on cement mortars with various GNP additions reveal compression strength enhancements of 3-27% and flexural strength increases of 15-82%, Lin & Du (2020). Less dramatic enhancements have been reported for concretes. Matalkah and Soroushian (2020) examined concrete with a water to cement ratio of 0.48, a GNP dosage of 0.16% by weight of cement increased the compression strength by around 14%. Wang et al (2017) tested cement mortar with a GO dosage of 0.08% by weight of cement and observed a 27% and 16% increase in the flexural strength and compressive strength respectively. Arkash et al (2021) tested high strength concrete with a GO addition of 0.15% by weight of cement and obtained increases of 13% in both the flexural and compression strengths, further increases were obtained by the combined use of GO and micro-silica. Bardwaj and Kumar (2021) tested geopolymer concrete with GO addition of 0.05% by weight of binder, increases in compression strength of around 20% were observed, with similar enhancements in tensile and flexural strengths. Although appreciable increases in both tensile and flexural strength are reported in the literature for GEC, it should be noted that there is no change in the ultimate failure mode, i.e. GEC remains a brittle material. Hence in applications involving significant tensile stresses, rebar will be required.

In many of the aforementioned existing studies, the number of specimens examined and the associated variation in results is not reported. Of those giving such detail, Matalkah and Soroushian (2020) stated their results were based on the average of 3 specimens, however no standard deviation values were given. Similarly, the results produced by Bardwaj and Kumar (2021) were based on the average of 3 samples, a standard deviation of < 5% and <10% was reported for the compressive strength and flexural strength results respectively.

Across the existing data, a threshold of graphene dosage has been observed, beyond this point, the influence of graphene on mechanical properties may be negative. For the case of pristine graphene in cementitious materials, the review by Lin & Du (2021) indicates the optimum dosage lies between 0.02% to 1% by weight of cement. This threshold may in part be due to the reduced dispersion capability at higher dosages.

Whilst the existing studies demonstrate the potential of GEC, the observations are confined to laboratory scale specimens. With a view to understanding the practicalities of GEC production and use on a construction level scale, a programme of experimental work and field studies on the use of GEC was conducted as part of an Innovate UK funded project over the course of 12 months from 2021 to 2022. The work was in partnership between the University of Manchester’s Dept. of Mechanical, Aerospace & Civil Engineering, the Graphene Engineering & Innovation Centre and industry partner Nationwide Engineering Ltd. The next sections give an overview of some of the key findings of the experimental work and field studies.

EXPERIMENTAL PROGRAMME:

Starting with a control mixture based on a standard C28/35 concrete specification with a water to cement ratio of 0.54 and an OPC binder classified as CEM1 in accordance with BS EN 197-1 (BSI 2011), the effect of graphene nano-particle addition on the resulting concrete’s mechanical properties were investigated in accordance with BS EN 12390 (BSI 2009, 2019a,b, 2021). In order to ensure reliability of the results, for each of the mixtures tested and for each mechanical property, 9 specimens were produced i.e. 3 specimens were taken from 3 separate batches. Across the various mechanical properties measured, a maximum standard deviation of around 10% was observed within the batches which points towards a good level of consistency and repeatability. Various dosage rates of graphene nano-particles were examined, these were within the optimum range described in the previous section. In total, approximately 2000 mechanical tests were conducted. The graphene products were dispersed in water using mechanical mixing and the resulting solution was added to the wet concrete mixture. Across the various GEC mixtures examined, enhancement in all strength properties were observed, with increases approaching 30% in both compressive and tensile strength typical. The graphene admixture was also seen to improve the early strength development of the concrete. The results in Figure 3 can be read as typical of the GEC mixture performance.

Whilst the use of graphene can accelerate strength development as shown in Figure 3, the workability of the wet concrete is reduced, hence in the use of a superplasticiser may be necessary to counter this, in the present work a polycarboxylate based superplasticiser was adopted.

FIELD APPLICATIONS:

The first sizeable application of the formulated GEC was for a ground bearing slab at the Solstice Park Development in Wiltshire, UK, constructed during May 2021. The slab was laid on a compacted subgrade with a minimum CBR of 15% and was designed for an imposed load of 30 kN/m^2. A C28/35 CEM1 type mixture similar to the control in the aforementioned experiments was used in combination with the preferred graphene mixture identified in the experimental campaign, this resulted in an unreinforced slab, 150mm thick. An area of approximately 17m x 14m of GEC slab was cast in one pour, an immediately adjacent ground slab bay without graphene was also cast at the same time, see Figure 4. The graphene solution was applied at the local batching plant, the approximate time between batching and the pour was less than 1 hour. Specimens taken from the GEC batch exhibited strength enhancements over the control concrete consistent with those observed in the laboratory trials.

A series of k-type thermocouples were installed in both slabs to gain an understanding of the heat of hydration, output from thermocouples located centrally within each type of slab bay is shown in Figure 5. At early hydration stages, the GEC slab exhibits a higher heat release compared to the control slab during the first 40 hours. This effect can be attributed to the acceleration of the hydration reactions and the rapid formation of the hydrated products resulting from the increase in nucleation sites as previously described. To date, the GEC slab has performed well with no visible cracking in evidence. Since the Wiltshire project, a number of large ground slab pours have been conducted using the GEC formulation, the largest pour to date being 1200m^2.

CONCLUSIONS:

The preceding sections have demonstrated the repeatability of GEC performance from laboratory to construction level scale. Ensuring uniform dispersal of the graphene nano-particles within the wet concrete mixture and hence avoiding agglomeration is pivotal in obtaining consistent performance in the hardened concrete. Further research is required on the development of optimum graphene product additions and the associated mechanisms for addition in order to develop the full potential of GEC. Nevertheless, as the relative cost of graphene products decrease in parallel with increased quality and volume of manufacture, GEC presents itself as a viable means of reducing the carbon footprint of concrete construction. According to Goodisman et al (2020), the average cost of graphene oxide from leading manufacturers was around $1000/kg at a production rate of 10kg/day in 2020. Work undertaken by the same authors at the University of Pennsylvania, demonstrated the ability to significantly reduce these costs via large scale production, with output rates of 1 ton/day resulting in a commercially viable cost of $26/kg. At such a price point, the use of graphene products in concrete at construction level scale becomes realistic. In the case of the ground slab application described earlier in this paper, additional cost from the graphene products was offset by the reduction in total concrete volume required. Flexural strength often governs ground bearing slab design and the strength enhancements being realized with GEC mixes mean thickness reductions of 15% or more are possible. Such reductions in concrete volume constitute significant cost savings in large slab pours in addition to associated benefits for the carbon footprint.

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LIST OF FIGURES:

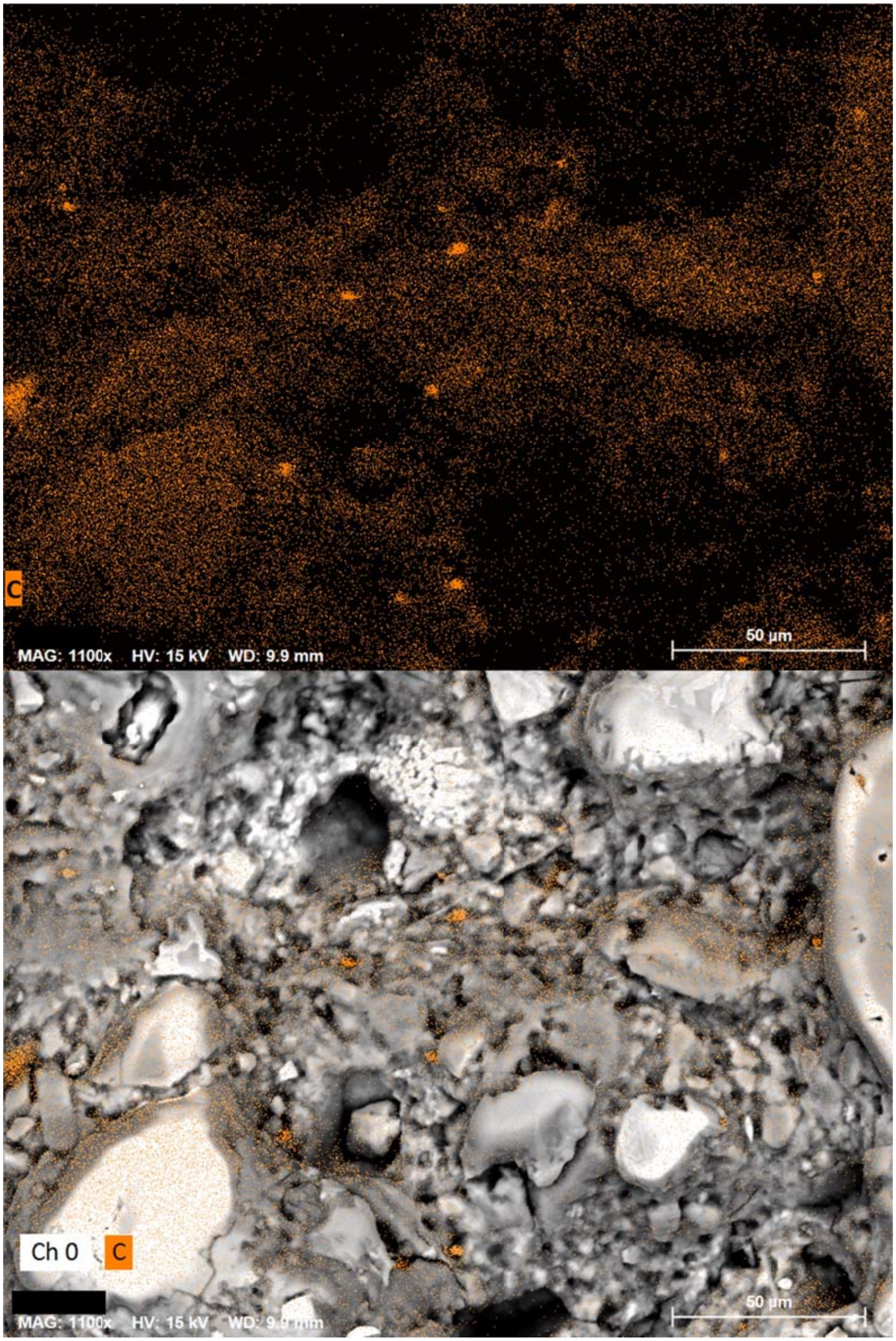

Figure 1: Energy Dispersive X-Ray (EDX) images showing graphene nano-particle dispersal and agglomeration in concrete, top image shows graphene only for clarity.

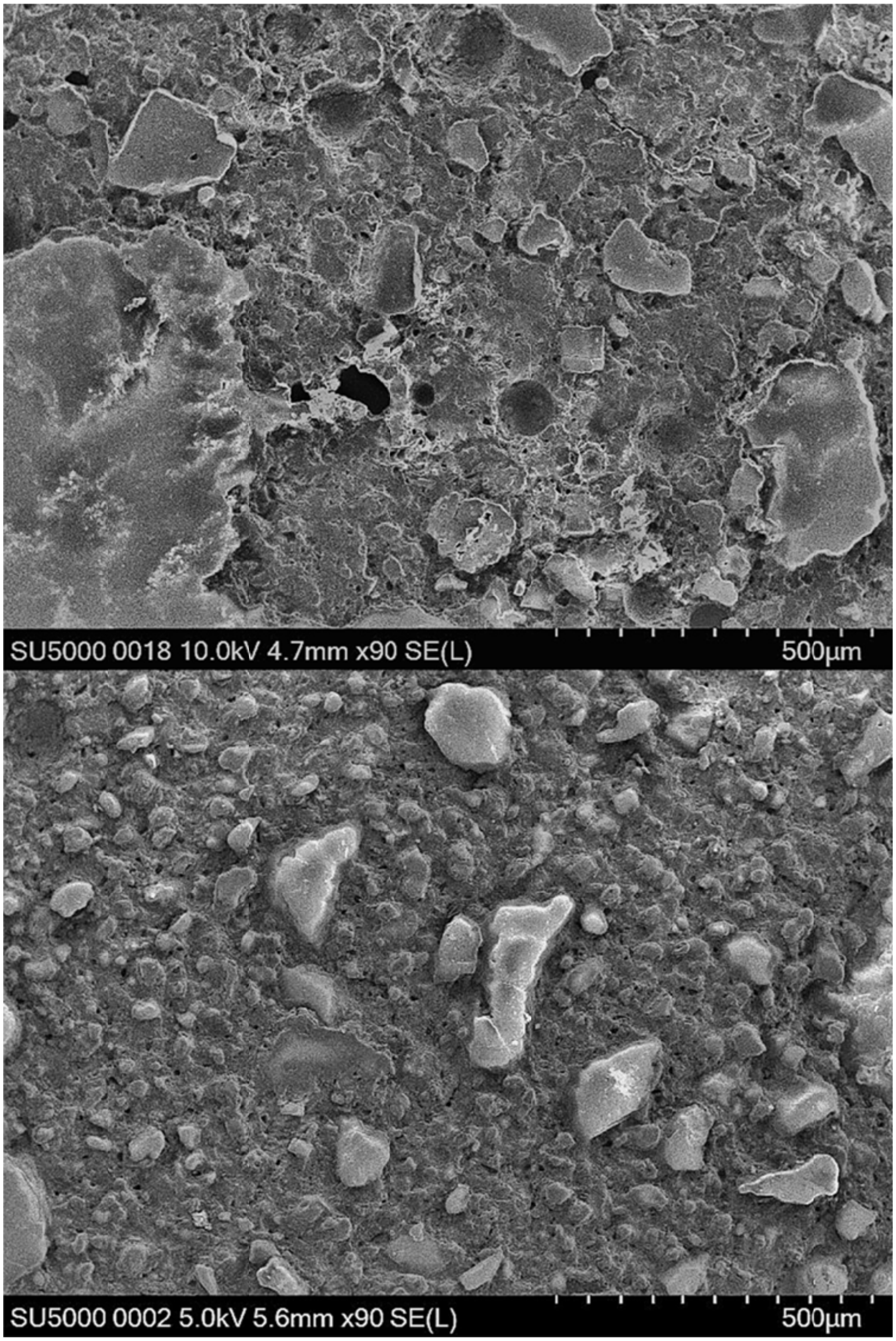

Figure 2: Scanning Electron Microscope (SEM) images; control concrete showing presence of micro voids (top), GEC with filler effect in evidence (bottom).

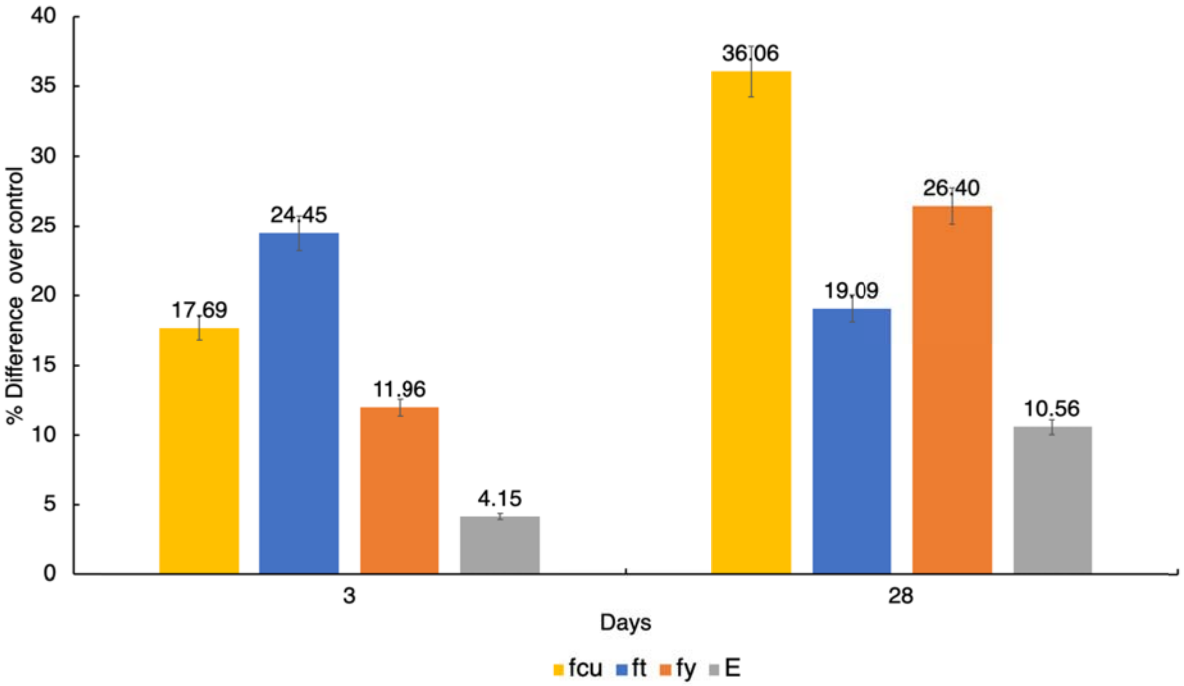

Figure 3: % increase for a typical GEC mix compared to corresponding properties of the control at 3 and 28 days for compressive cube strength (fcu), split cylinder tensile strength (ft), flexural strength (fy) and Young's modulus (E)

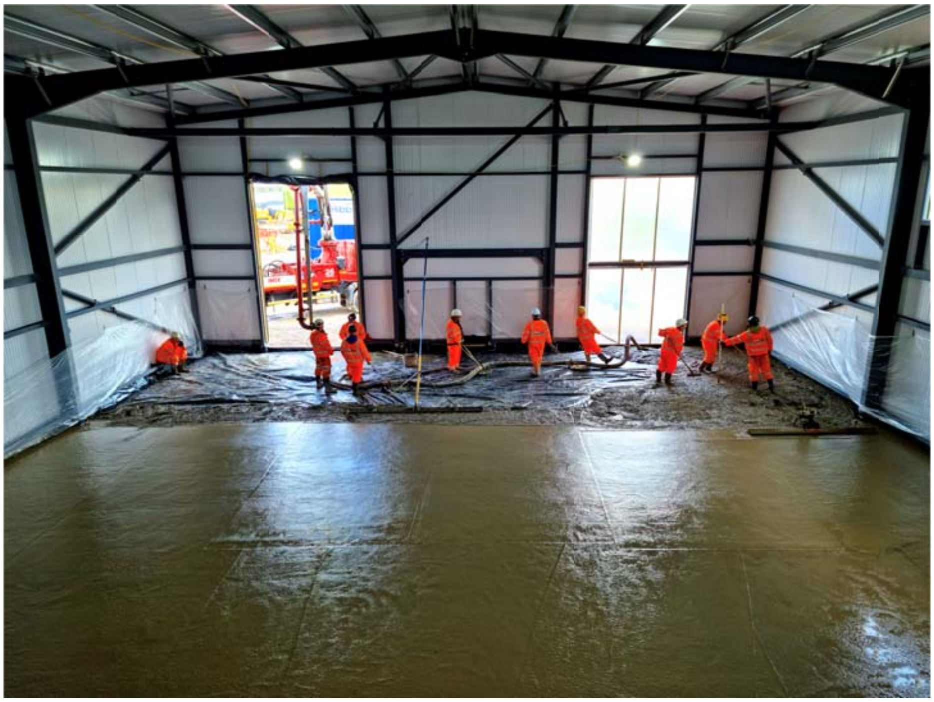

Figure 4: Solstice Park development; slab pour underway

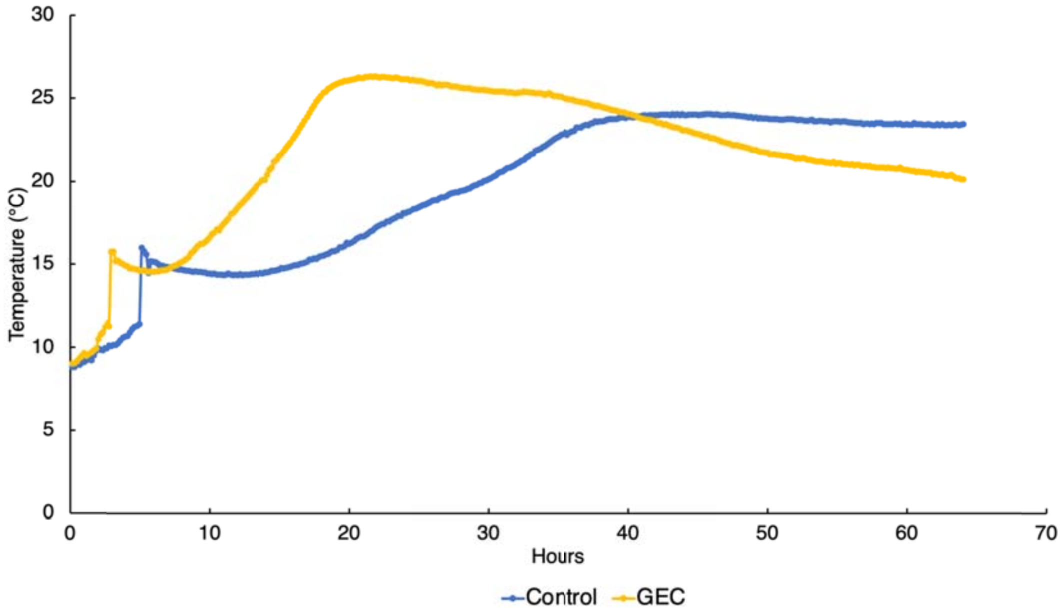

Figure 5: Comparison of thermocouple outputs from field application