TRANSFORMING THE FOUNDATION INDUSTRIES

Delivered by Innovate UK and EPSRC

## Transforming Foundation Industries Network+

# Small Project Summaries and Impact


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# Introduction

### Dr Bruce Adderley - Challenge Director - Transforming Foundation Industries at Innovate UK

The UK and the rest of the world relies on materials produced by the Foundation Industries. From the bricks, cement, metals, and glass used in our homes, to the cups and saucers (ceramics) for your morning tea or coffee, washing up liquid and detergents (chemicals), and paper packaging for wrapping birthday presents. It is, therefore, essential that these industries are a sustainable part of our society long into the future.

This is why the Transforming Foundation Industries Network+ was created as a critical part of our wider Challenge. Designed to bring through new avenues of research across multiple disciplines and industries, and to give opportunity to those now early in their career but who will deliver what we need over the coming decades, this brochure demonstrates the success that this programme has been.

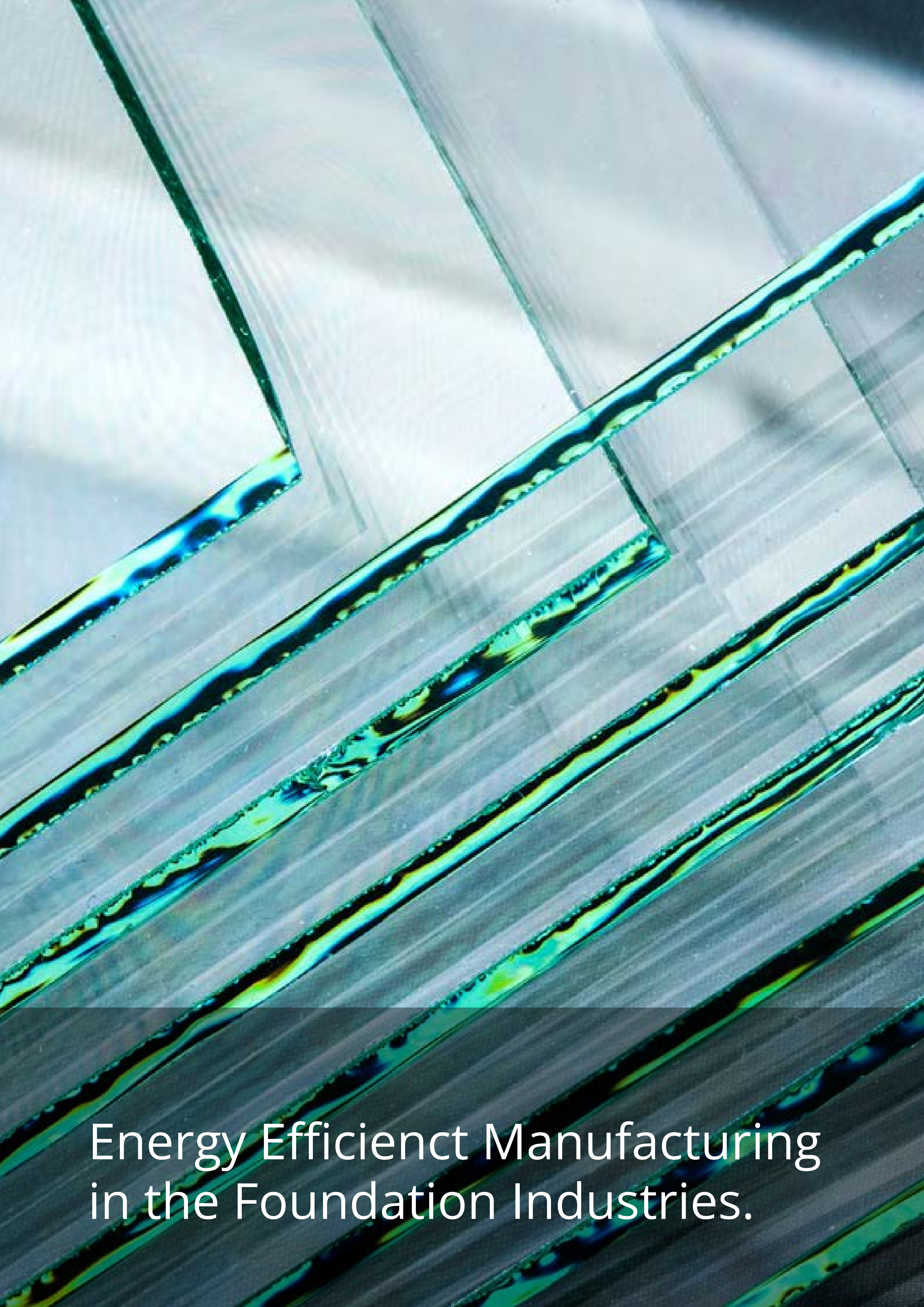
So, I express my thanks to Ian Reaney and his team for all they have achieved and hope, like me, that you will find the projects described here not just interesting, but exhilarating, as we continue to support the Foundation Industries on their journey to a sustainable future.

### Professor Ian Reaney - TFIN+ Director

The UK's Foundation Industries, which include ceramics, glass, cement, metals, paper, and chemicals sectors, constitute over 7,000 companies, over 250,000 employees, with a revenue of greater than £67.5 billion that is further boosted by the wider UK supply chain. However, they are responsible for 10% of the UK's $CO_2$ emissions and are the biggest consumers of fossil fuels. The UK Committee for Climate Change's roadmap for reducing carbon emissions to net zero by 2050, emphasises the crucial role of various large scale technologies, including carbon capture & storage, hydrogen, and electrification, but Resource Efficiency and Energy Efficiency (REEE), which includes recycling, resource conservation, material substitution, and the introduction of energy-efficient processes, accounts for close to one-third of emissions reduction and until 2035 is the largest contributor to carbon mitigation.

The Transforming Foundation Industries Network+ has strived to build a community that can work together to find common solutions to these challenges. Here, we collate the outputs of our 33 completed projects. They cover innovations in the key themes required to create sustainable foundation industries, including energy efficiency, resource efficiency, policy, advocacy and equality, diversity and inclusion. They have been co-created by academia and industry and many of the outputs are already embedded within the collaborating companies. It is a testament to the hard work and dedication of my colleagues and the wider academic and industrial community that we have been able to achieve these outputs in such a short space of time.

Please note: Projects funded under the Enablers of Transformation call are still active. Results of these projects will be included in an updated version of this brochure, as well as on the TFIN+ website.



# Energy Efficienct Manufacturing in the Foundation Industries.

# Feasibility study on valorisation of paper mill sludge (PMS) to manufacture Eco-bricks: Towards decarbonisation and sustainability in construction

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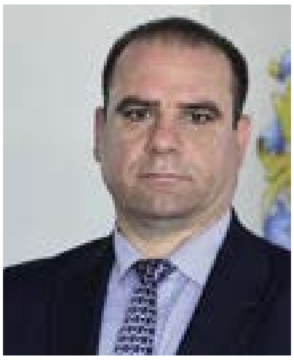
**In collaboration with StanRocc**

As with the other Foundation Industries, the pulp and paper industry is keen to develop more circular supply chains. Recycling paper is a more efficient use of resources and uses less energy than manufacturing paper from virgin pulp. The recycling process results in the generation of paper mill sludge (PMS) – essentially comprising very short paper fibres and the clays and fillers from the recycled paper. This project explored the feasibility of using this waste as an active ingredient in construction to produce fired clay bricks. Research focused on material characterisation of PMS and its corresponding use in value-added eco-bricks, wherein brick properties such as water absorption, apparent porosity and compressive strength of the bricks were determined. Embodied energy and CO2 release were calculated based on percentage of PMS added. Results revealed the presence of silica, calcium carbonate and other important minerals useful in the fabrication of bricks.

The mechanical properties of the bricks reduced with increasing PMS concentration, due to an increase in apparent porosity but there was a commensurate reduction in $CO_2$ emissions and embodied energy. For >10 wt% PMS excessively high-water absorption values and low compressive strength suggested that the bricks no longer conformed to the standards of conventional clay products. However, bricks with <10 wt% PMS were viable and point to a potential pathway of reducing landfill waste within the paper industry whilst simultaneously reducing the carbon footprint of materials for the construction industry.

# Investigation of a flat heat pipe for high temperature waste heat recovery from metal slabs



**Professor Hussam Jouhara, Brunel University**

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**In collaboration with Econotherm**

Energy efficiency is among the most important keys to unlock a green and more sustainable economy and a substantial amount of energy can be saved via the reuse of waste heat. Exploitation of waste heat streams has already been investigated mainly relying on forced or natural convection as a heat transfer method. However, waste heat is also available as a radiative source. Radiative heat sources pose real challenges due to the complexity of modelling, its intensity and the status of current technology. Indeed, no technology can currently effectively recover radiative waste heat sources.

Brunel has developed a novel radiative Flat Heat Pipe (FHP) heat recovery system to capture high temperature waste heat such as from slags, and slabs. The FHP relies on two phase transfer to passively move heat from the hot to the condenser section. The heat is then transferred safely to the heat sink such as air, water and water-glycol. The FHP system was designed according to a thermal/electrical analogy, was constructed with the support of Econotherm Limited and prepared for testing. Testing was carried out in an industrial environment and for a heat source of 450 °C. The FHP was able to recover up to 800 W/m$^2$ with an average evaporator surface temperature of 45 °C, highlighting its potential for even higher temperatures.

The results of this industrial test, along with validation of the FHP model, allowed Brunel to assess further potential utilisation. It was concluded that the FHP technology could be easily implemented in the steel industry, for example, in the manufacture of wire which is extruded and cooled down by forced convection and radiation on long conveyors. If applied to the entirety of the conveyor, the expected output from the FHP system is predicted to be 12.5kW/m$^2$. The aim is to further develop the technology to full demonstration scale, initially in the metals sector which presents strong potential for FHPs due to the high temperature and available heat sinks but also in cements. The built environment relies upon the metal and cement sectors for much of its materials. Heat recovery in these energy intensive industries is of vital importance if we are to continue to manufacture in the UK. This is true irrespective of the introduction of low carbon or carbon neutral energy production in the future.

Right: Flat heat pipe system, prior to installation (top) and in a wire manufacturing plant (bottom).





# Valorisation of foundry sands as medium-high temperature waste heat recovery material

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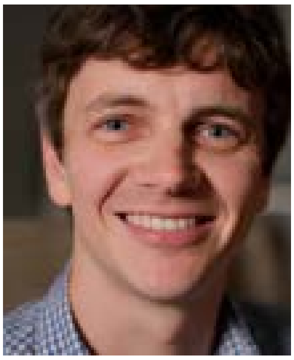
**In collaboration with Kelvin Thermotech, Confederation of British Metalforming**

The industrial sector in the UK accounts for ~17% of its overall energy consumption, the majority of which is in the form of heat (BEIS, 2017). Waste heat recovery (WHR) and reuse are thus the next frontiers for energy-intensive industries. Thermal energy storage (TES) is a cost-effective and versatile solution for WHR. Latent heat TES (LHTES), based on the isothermal heat absorption/release during phase change, is a promising sub-category of TES. THERMCAST demonstrated the technical and economical feasibility of using foundry sand as a TES material for medium-high temperature waste heat recovery and storage. The project developed a novel thermal energy storage (TES) material based on foundry sand for hybrid thermal energy storage up to 400 °C. The optimal composition consisted of 60% $NaNO_3$, 30% foundry sand and 10% further additives. The material had good chemical and physical stability after 50 cycles (25-400 °C) with energy storage density, 566 kJ/kg, and thermal conductivity, 1.23 W/mK. A TES system, based on the developed material, was designed using the waste heat data which gave 87% and 81% efficiency for charging and discharging, respectively. Preliminary technoeconomic analysis suggested that a minimum payback period of ~5–6 years with 90% system efficiency.

THERMCAST, therefore, showcased an alternative utilisation pathway for waste foundry sand as a thermal energy storage material. It demonstrated all the steps necessary to bring this technology to the market and evaluate its potential for energy-saving. Its theoretical implementation in a TES device was realised within an industrial setting in the co-sponsoring company. Throughout THERMCAST several UK companies and academics were approached to encourage more entities to further explore this technology in the future.

Right: The exhaust of one of two metal melting furnaces in Boro Foundry (top); Ladle preheating using flue gas.


# Improved energy efficiency of float glass production



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**In collaboration with Pilkington NSG**

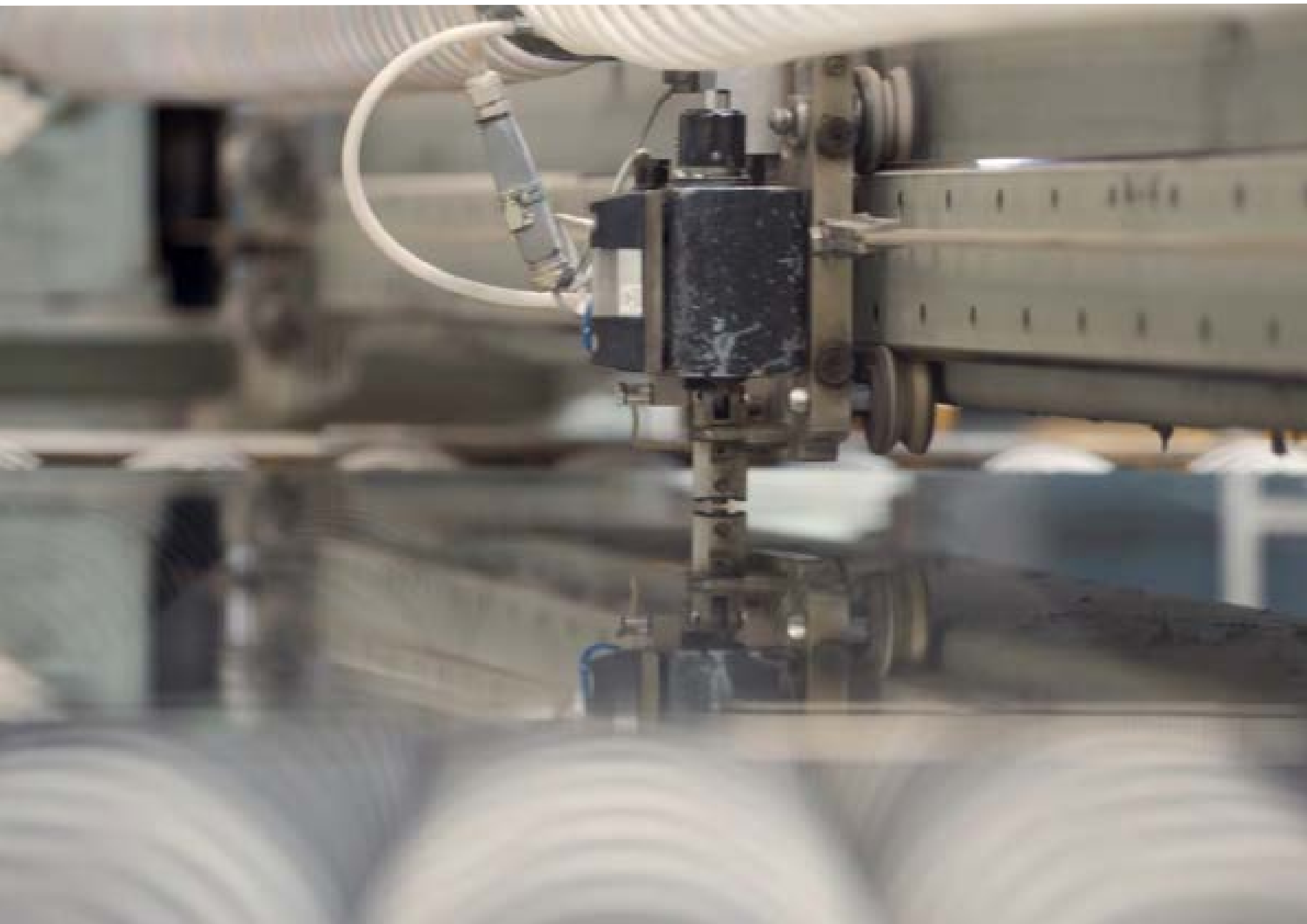
Of all the 'enablers' of transformation, digitisation and control offers the greatest potential to impact across multiple FI sectors and its benefits of reduced plant downtime and energy and raw material savings are clear. Implementation, however, deviates significantly from the classic skill sets associated with the Foundation Industries, requiring knowledge of advanced computing, sensing, modelling and data handling.

In the built environment, glass is pivotal in modern construction with ten million tonnes of float glass produced in Europe every year, with the UK currently having a 6% share of European glass production. Pilkington United Kingdom Limited, part of NSG Group, is a leading UK glass manufacturer and supplier with around 3,000 staff across the UK and producing a wide range of glass solutions (glass for architectural applications, solar panels, automotive equipment, touchscreens etc.) Being an energy-intensive manufacturing process and noting NSG Group's aim to achieve a 30% reduction in $CO_2$ emissions by 2030, this project explored the development of a data-based model which can, ultimately, be used to increase the efficiency of the float glass production.

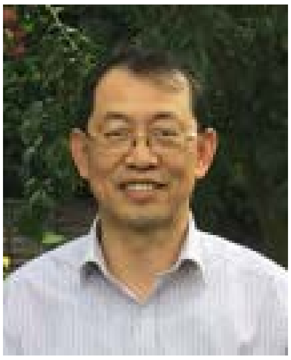
This study involved the development and deployment of a machine learning model which, having been trained on data gathered from 100s of sensors at the UK5 float glass plant in St. Helens, was used to predict variations in product quality up to 72 hours into the future. The overall model was formulated using a Gaussian 'product of experts' approach, whereby separate models are each used to cover different regions of the input space before predictions are formulated using a weighted product of all models.

The model is able to function in an online setting (allowing it to be updated using the most recent data from the UK5 plant). The model can be used to form different decision support tools (e.g. the optimiser, sensitivity analysis) to help increase the efficiency of float glass production. The approach is scalable to large datasets and, to the best of our knowledge, generic in that it can be extended to other float glass furnaces. NSG has directly funded another six months of research which has already been transferred into the Manufacturing Execution System used at the UK5 plant.

Right: Float glass production.
Images courtesy of Pilkington UK, part of the NSG Group.

# Using blast furnace waste heat to convert various wastes into new raw materials for low energy glass manufacturing



**Professor Zushu Li, University of Warwick**

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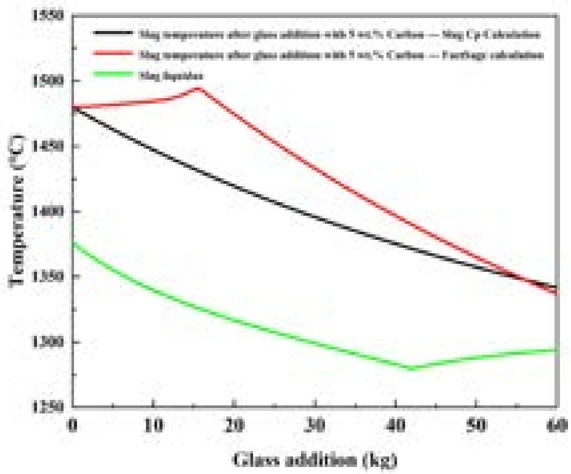
**In collaboration with British Glass, Glass Futures, Calumite Ltd, Materials Processing Institute**

Energy-intensive industries such as glass manufacturing and steelmaking face significant challenges in reducing energy consumption and $CO_2$ emissions. For example, heat during blast furnace hot metal and slag tapping dissipates into the atmosphere and is currently not recovered/ utilised and, in glass manufacturing, a significant amount of energy is consumed in raw material preparation and melting with $CO_2$ released from the decomposition of carbonates.

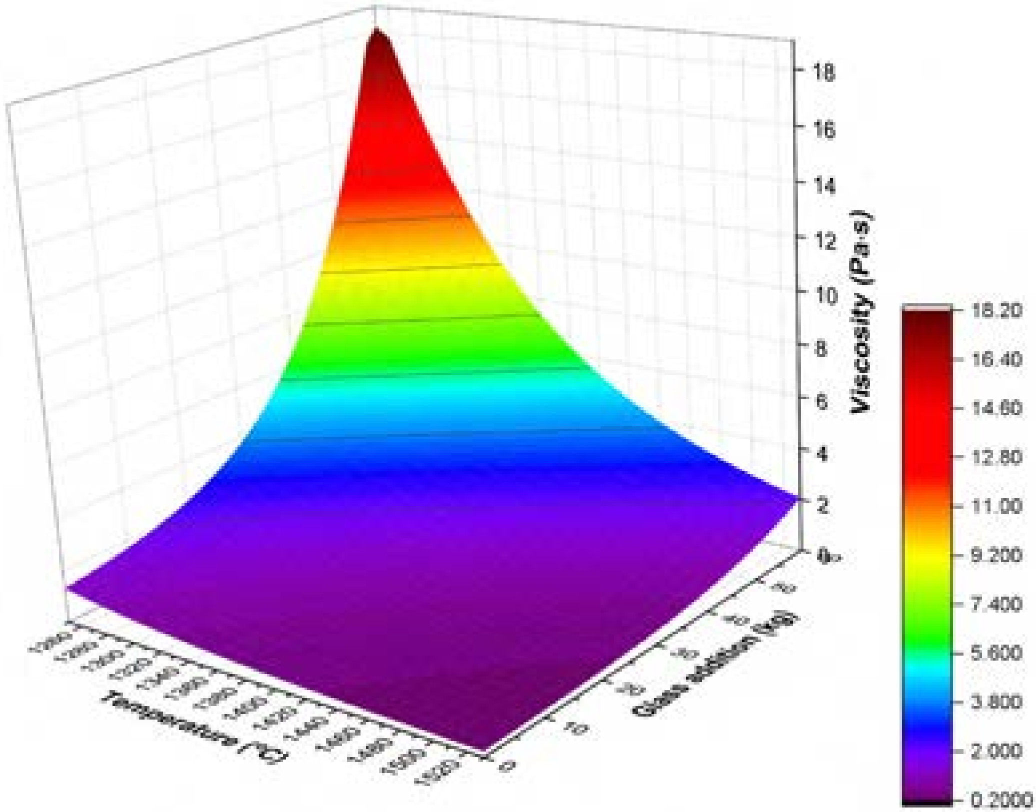
This project investigated the possibility of developing an innovative process for utilising the blast furnace waste heat to convert contaminated recycled glass streams to high value raw materials to reduce energy, virgin raw materials consumption and $CO_2$ emissions. The results are considered particularly beneficial for hard-to-use/recycled wastes such as contaminated glass streams.

Mass and heat balance and thermodynamic modelling determined how much waste may be utilised and its impact on operational parameters such as melting temperature and viscosity. The results suggested that up to 50 kg waste glass may be added to 100 kg molten blast furnace slag under ideal operating conditions. The first figure shows the effect of the addition of contaminated waste glass containing 5% organic waste on the slag liquidus (green line). The liquidus temperature of the new slag decreased with increasing waste glass addition.

The second figure shows the impact of waste glass addition on the viscosity of new slag and demonstrates that with up to 50 kg waste glass added to 100 kg blast furnace slag at a practical operating temperature of 1400 °C, the viscosity is less than 4 Pa·S. Our data suggest, therefore, that under an industrial scenario (with strong stirring caused by injection) the dissolution of waste glass will not be a limiting factor and the process is technically viable. Our findings have been shared with industrial partners during the execution of the project, who, along with the PI, have been exploring ways to up-scale the process.




Above: The effect of the addition of contaminated waste glass containing 5% organic waste on the slag liquidus (green line).




Above: The impact of waste glass addition on the viscosity of new slag.

# Resource Efficiency, Recovery and the Circular Economy.

# Valorisation of metallurgical wastes through chemically bonded ceramic (VMW-CBC)

**Dr Sam Adu-Amankwah, University of Aston (research conducted when at University of Leeds)**

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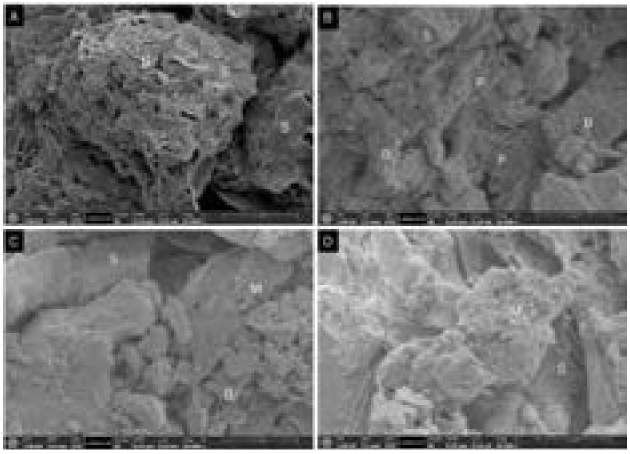
**In collaboration with Luxfer MEL Technologies**

In a circular economy, by-products retain some value since they may feed into other production processes but feasibility of their use hinges on the availability of symbiotic manufacturing sectors as well as cost effective repurposing strategies. These do not exist for most by-products from the Foundation Industries and waste streams are often mixed.

This project explored thermal and chemical repurposing methods for magnesium-rich by-products with the aim to produce reactive magnesia for ceramics for repair applications. Optimal treatment was attained at 500 °C at which point reactive magnesia formed. Above this temperature, compounds crystallised to the less reactive, periclase MgO phase. The magnesium-rich sludge did not react upon exposure to enforced $CO_2$, which limited the scope for cost effective chemical valorisation. The reactivity of the thermally treated MgO and the resulting mechanical properties of the ceramics were compared with a conventional raw material, referred to as burnt magnesia. Impurities in unsegregated waste streams modified the reaction and products formed but mixing with alloying oxides such as $ZrO_2$ improved ceramic quality.

This project has therefore demonstrated the feasibility of using metallurgical wastes for ceramics for repairs and has provided valorisation protocols and identified the role of constituents from other waste-streams that may be used to enhance performance.



Above: Scanning electron micrographs showing magnesium phosphate cement prepared from (a) burnt magnesia, and MgO-rich metallurgical by-product treated at (b) 200 °C, (c) 500 °C and (d) 1000 °C.

# Sustainable investment assurance model (SIAM)

**Dr Stephen Spooner, University of Coventry (research conducted when at Swansea University)**

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**In collaboration with CR Plus Ltd. and BSI**

The project extends the multifaceted sustainability modelling from steel to other Foundation Industries. Consultation with each sector was conducted to review the existing SIAM framework and adapt measurements concerning circularity, direct/indirect energy consumption maps, economic drivers versus policy constraints and proportional representation of workers, working conditions and wealth disparity. The primary outcomes are summarised:

i) Decarbonisation/sustainability improvements from environmental perspectives are significantly skewed to the use of additional energy requirements for either heat, transport, or reduction of material. The UK has a relatively well-developed renewables portfolio on the grid, however over short time scales an increase in energy demand can only be met through the use of non-renewable energy production methods. Consequently, until further development of a renewable energy grid with overcapacity is achieved there is minimal gain to be made from altering production methodologies.

ii) Volatility in supply chains is a major factor which can affect every aspect of sustainability. Without control and consistent supply of materials, validation and representation of sustainability credentials is not only meaningless but potentially unethical to provide to consumers as a purchasing motive. Supply chain volatility is a big risk factor, and creates an economic reluctance to both invest from an initial financial basis, but also from a point to minimise further disruption from current manufacturing methodologies. De-risking supply is another overarching theme which must be tackled to shift to sustainable practices.

iii) Data quality continues to be an issue. Known data from the literature was inputted into databases when available but over 75% was obtained from open-source unverified literature. Such data collection is time consuming and expensive but with investment in capex across multiple industries a necessity to meet sustainability targets, it is essential. If integrated from the outset, significant improvements could be made and realised with minimal cost and impact.

Current discussions are ongoing with industry on how to quantify sustainability improvements of future capex investments. A limited version of the SAIM framework has been supplied to government organisation for internal use on investment decision making. The tool is also being openly used within several large companies to validate sustainability investment plans both in the UK and international operations. The benefit of SIAM to the built environment is to facilitate informed decision making amongst stakeholders such as industry, national and local government and construction companies in their drive to reduce the carbon footprint.

# Sustainable replacements for coal tar pitch binders

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**In collaboration with Morgan Advanced Materials**

Coal Tar Pitch (CTP) is a residue formed from the distillation of coal tar and is widely used as a carbonisable/graphitisable binder to form carbon electrodes (*e.g.* for aluminium smelting), seals, specialty graphites for electric brushes and current collectors (*e.g.* wind turbine generators & rail pantograph systems), and molten metal-conveying components for the metal industries. However, CTP is fossil-derived and toxic and has recently been classified as a 'sunset' status material under REACH such that identification of a sustainable alternative is essential for the Foundation Industries dependent on these carbonised/graphitised materials. Wood Tar Biopitch (WTB), obtained from distilling sawdust at temperatures up to 1,000 °C under an inert atmosphere, shows promise as a safe and renewable binder. However, despite several decades of academic interest, socio-economic drivers are only now sufficient for its key shortcomings to be addressed. From a sustainable CTP alternative perspective, these shortcomings include low carbon conversion yields, obstacles to translation to existing manufacturing processes (*e.g.* poor impregnation and extrusion), insufficient binding to particles and relatively poor properties of the resultant materials.

During this project, we worked closely with Morgan Advanced Materials to produce WTB from distilling sawdust and establish a reliable source. The WTB was then mixed with graphite particles and subsequently carbonised and graphitised to produce carbon-carbon composites following processes typically used in industry for the fabrication of their CTP based products. Building on this exploratory project, a follow-on grant funded by EPSRC via Henry Royce Institute (Industrial Collaboration Programme, ICP) was awarded to this academic-industry team to continue exploring the replacement of CTP by a more sustainable binder. This follow-on funding allowed us to develop strategies to refine the composites chemical formulations and improve the microstructure, levels of graphitisation and, hence, the properties of the carbon-carbon composites based on WTB during carbonisation/graphitisation.

These two projects have helped accelerate the replacement of a sunset fossil derived chemical (CTP), with a bioderived chemical with reduced toxicity (WTB) through both establishing a reliable WTB source and providing a deeper understanding of the underlying materials chemistry of WTB.

Left: Wood Tar Biopitch (WTB) synthesised from sawdust.

# SANDTHERM: Deployment of a novel medium-high temperature waste heat recovery unit based on foundry sands

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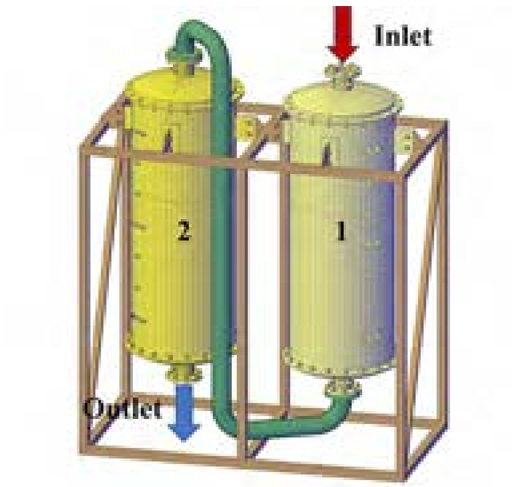
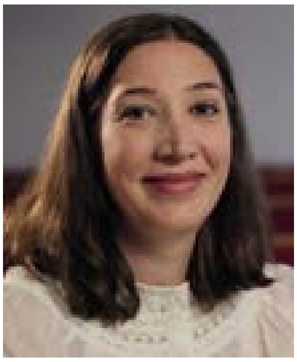
**In collaboration with Kelvin Thermotech, Mantec Technical Ceramics and the Boro Foundry**

SANDTHERM demonstrated the technical and economic feasibility of using waste foundry sand (WFS) as a thermal energy storage (TES) material for medium-high temperature waste heat recovery applications. It deployed, operated and monitored a waste heat storage and reuse unit using TES materials containing WFS. This novel material was composed of 40% phase change material (PCM), 20% WFS and 20% MgO. Two PCM's were selected to improve system efficiency by maximising latent heat. These were $NaNO_3$ and a 60-40 $NaNO_3$-$KNO_3$ mixture with melting points of 309 °C and 218 °C, respectively. The materials had a density of 1.65 and 1.93 g/cm$^3$, average specific heat capacity 1.23 J/gK and 1.22 J/gK and average thermal conductivity, 1.63 W/mK and 1.48 W/mK for $NaNO_3$ and 60-40 $NaNO_3$-$KNO_3$, respectively. The device was charged using a high temperature fan with an average mass flowrate of 0.028 kg/s and an inlet temperature of 400 °C, which was the maximum capacity of the 10 kW heater. Total charging time was 10h followed by a total discharging time for 24h. System efficiency was 76.1%. A robust, computationally inexpensive CFD model was able to predict system efficiency and using UK pricing the payback time was approx. 15 years. Improvements in efficiency to 90% coupled with more competitive global material and manufacturing pricing suggest the potential to achieve a payback period of approx. 5.6 years. The PI has obtained follow-up funding under Marie Skłodowska-Curie Actions (101068507) to extend this process to other foundation industry waste materials. He has disseminated the data to several leading companies and presented the results at conferences and in peer reviewed journals.




Above: Figure illustrating the setup of the Thermal Energy Storage system, composed of two carbon steel tanks connected in series. Inlet is located at the top of tank 1 and outlet at the bottom of tank 2. The first tank was filled with WFS CPCMs.

# Paper and construction industry symbiosis via anaerobic digestion for enhanced resource efficiency and a low carbon future.



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**In collaboration with SAICA**

The UK is home to ~50 Pulp and Paper Mill companies with over 80 associated businesses. The pulp industry is one of the UK's most energy intensive industries and requires novel decarbonisation processes to maximise energy and mass efficiency. As part of the paper recycling process, over 10% of input materials becomes paper sludge, a non-hazardous biowaste. In this project, we proposed a more resource efficient circular approach, that consists of two stages. The first stage redirected paper sludge away from incineration towards biogas using anaerobic digestion, as a form of low-carbon energy for cogeneration (CHP). The research results indicate that paper sludge had a methane potential of 163 ml $CH_4$ per gram of volatile solids and a 48% biodegradability. Paper sludge therefore has remarkable anaerobic digestion potential that could be applied across the paper industry as a standalone process. The second stage of the project utilised the remaining slurry fraction after anaerobic digestion, called digestate, as a water replacement in concrete manufacture. The concrete formed using up to 50% substitution resulted in increased compressive strengths up to 46 and 35 MPa after 90 days, respectively with and without the use of plasticiser. The combination of suspended solids and dissolved ions greatly improved the structural rigidity of the concrete and could potentially be used not only as a waste disposal method, but also a beneficial concrete additive. Overall, the combined anaerobic digestion and concrete application valorised paper sludge for use within a wider circular economy.

# Innovative green process to turn alkali solid wastes into carbon-negative feedstock for the cement industry

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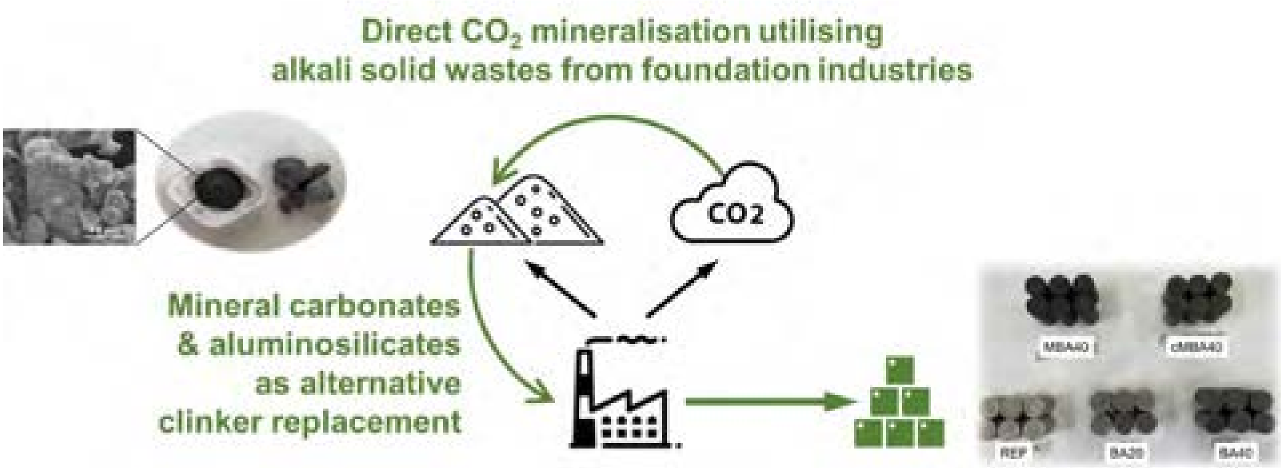
**In collaboration with the Materials Processing Institute and Aggregate Industry/London Concrete**

Over 2 billion tonnes of diverse alkali solid wastes (i.e., biomass ash, cement kiln dust, steel slag) are generated from Foundation Industries worldwide annually and are primarily disposed of through landfills and stockpiling. The volume of these is expected to double in the next few decades, which has brought significant challenges to the cement and metal industries for reaching Net-Zero targets. This project developed an innovative green chemical process via mechanochemical activation to turn these alkali solid wastes into carbon-negative materials which can be used as an alternative feedstock for producing low-carbon sustainable cement. Mechanochemical activation improves the reactivity of polysilicates (i.e., akermanite), mineral phases commonly present in alkali solid wastes (i.e., biomass ash, steel slag), for direct carbonation under conditions that resemble flue gas conditions. The effectiveness of the mechanochemical treatment was controlled by milling time, ball to sample mass charge ratio, and water content. In particular, the amount of water during the mechanochemical activation had a significant effect on the crystallisation process and crystal structure of the carbonate salts formed during the follow-on direct carbonation processes. Alkali solid wastes treated with mechanochemical activation can be used as alternative supplementary cementitious materials (SCMs) to partially replacing cement clinkers, with up to 40% substitution giving satisfactory engineering setting times and strength. The research team is looking into the feasibility of scaling up this novel process from lab-scale. With the fundamental understanding of the mechanochemical treatment processes developed in this study, the technology may be transferred to other foundation industry sectors, such as paper and ceramics.




Above: Innovative circular green production processes. Eliminating the release of solid wastes and process $CO_2$ into the environment.

# Next Generation and Intelligent Processes for the Foundation Industries.

# Low carbon manufacturing of high-quality mineral wool using high-temperature steelmaking slags and high-silica wastes

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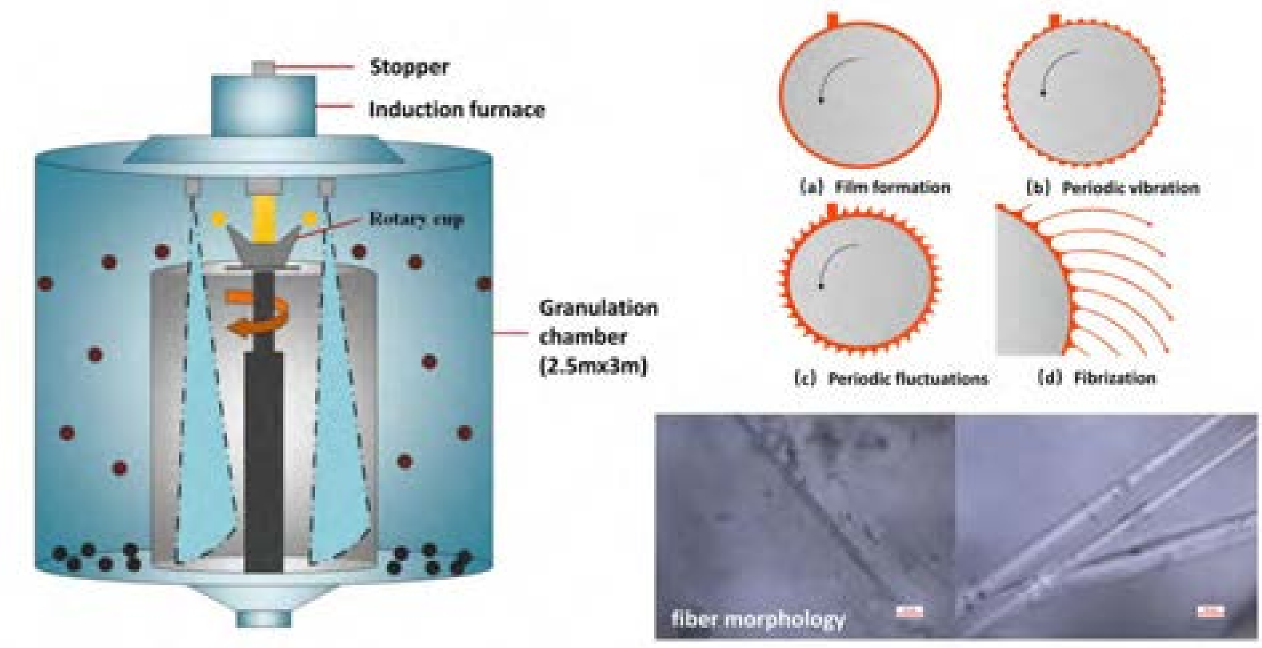
**In collaboration with Glass Futures**

A large amount of high-temperature steelmaking slag (1400~1600 °C) is produced during pyrometallurgical production. The heat (energy) carried by these slags is released into the atmosphere during the tapping process and is not used effectively. On the other hand, a large amount of heat is required to remelt the cold slag during manufacturing mineral wool, and high-silicon materials are added to facilitate fibrisation. This project investigated the use of heat from molten metallurgical slag and high-silica wastes to directly manufacture high-quality mineral wool to reduce energy consumption and $CO_2$ emissions.

The project focused on a modified mixture for the steel wool with a slag:glass:$SiO_2$:$Al_2O_3$ ratio of 4:4:1:1, as the melting temperature, viscosity, and composition meet the requirement of wool fibre manufacturing. It was found that for the production of one tonne of mineral wool, 400 kg of molten slag can be used, whilst utilising the heat from the molten slag, saving 13.65 kg coke per tonne of  wool production, thereby reducing $CO_2$ emissions by 50.04 kg/t wool.




Above: Schematic diagram of high temperature fibrisation device, fibrisation mechanism, and fibre morphology from the modified mixtures.

# Digital tools for agile waste segregation

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**In collaboration with the Centre for Process Innovation**

This project explored a method for non-destructive separation of various waste types at an industrially viable scale through instrumentation of a conveyor belt which will help the Foundation Industries to automate their waste segregation. The project demonstrated a novel idea of integrating a fast THz optical sensor with the roll-to-roll system for fully automated waste segregation.

The project investigated the most common types of plastic wastes used for industrial packaging: PVC, NBR, PP, PET and HDPE. THz time-domain spectroscopy was used to acquire the data and signal processing was used to remove background noise. The detector was mounted on a conveyor belt and the measurements were deployed in reflection mode. The measurements can be repeated for multiple points on each sample, in which the number of points depends on the speed of the conveyor belt and the size of the sample.

Although this feasibility study was performed on plastic wastes, it can easily be extended to other industrial wastes generated by the Foundation Industries, including metals, ceramics, glass, chemicals, paper and cement. This helps these industries develop industrial symbiosis such that the waste of one industry becomes raw material for another industry, thus promoting the circularity of the economy. In turn this protects the environment from pollution or contamination, making life more sustainable.

It is anticipated that the greatest impact of this work is the agility of this method in segregating wastes with a better confidence level compared to the other existing methods.

Above: Fast THz optical sensor with roll-to-roll system demonstrator.


INDUSTRY 4.0

# Micromachined based multi-sensing solution toward digitalisation of Foundation Industries

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**In collaboration with the Weir Group and the Materials Processing Institute**

Industry 4.0 and Industrial Internet of Things (IIoT) are driven by the expanding development of smart sensors that offer new approaches to collect and post-process data to improve factory operation and digitalise production processes. Substantial technological investment is required to realise digitalisation, leading to expansion of the global industrial sensors market to USD 53.2 Billion by 2030 with a compound annual growth rate of 9.06%.

The response of a new micro-electromechanical system (MEMS) sensor, designed to detect simultaneously two different gases using two mechanically coupled resonators (a bridge and cantilever), was simulated. The novel sensor design was subsequently submitted for microfabrication. Although the desired MEMS did not arrive in time to be part of the current project, an alternative device was sourced from the Fraunhofer Institute for Silicon Technology (ISIT) to illustrate proof of concept and to understand its dynamic response and ability to absorb gas.

Although the results were promising for sensing, an additional upgrade is required to achieve our targeted aim and we are currently investigating the capabilities of devices coated with metal-organic framework (MOF) for superior gas absorption and sensitivity. The project is continuing with internal funds and a new system will be tested once the novel sensor is characterised and validated in the lab using $CO_2$ and helium, followed by further trials at the Materials Processing Institute, UK laboratories.

The outcome of the simulation work was published in the Nonlinear Dynamics journal.

# Atomistic scale simulation of the magnetic anisotropy in steels

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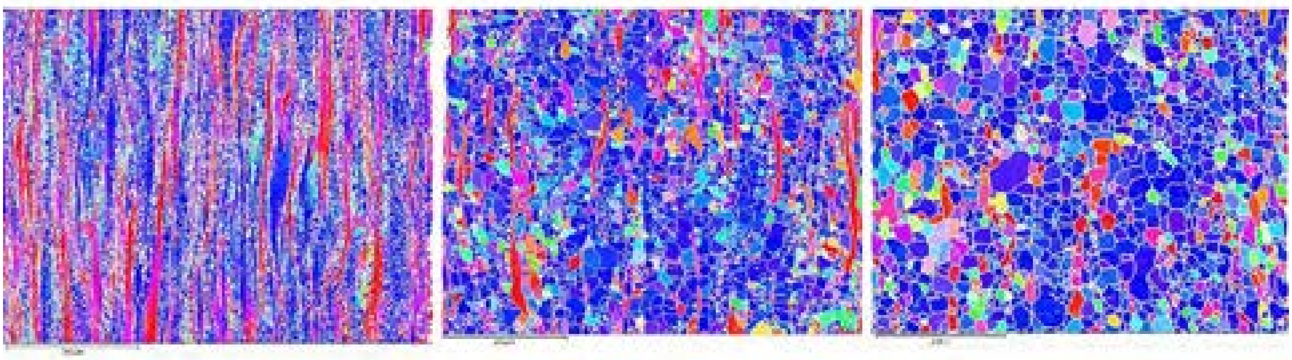
**In collaboration with British Steel, Tata Steel and the University of York**

Steel is an irreplaceable and highly recyclable material that serves as a cornerstone for Foundation Industries worldwide. Monitoring the steel production process closely is crucial to ensure sustainable development, growth, and modernisation. The microstructural parameters of steel must be controlled with great care to maintain its unique properties. Electromagnetic (EM) sensors present a tremendous opportunity to monitor and control these microstructures in real time. By optimising processes and energy consumption, increasing the recovery rate of downgraded products, and expanding the range of applications addressed by a single compositional grade, the deployment of real-time microstructure measurements can significantly enhance the sustainability of the steel industry.

One area of particular interest in steel microstructural parameters is grain orientation, which determines a material's resistance to deformation in a specific direction, known as the r-value. Researchers have developed a fundamental modelling capacity to correlate texture with magnetic properties, producing crucial data on magnetic parameters for crystallographic anisotropy in steels. This data will enable the use of EM sensors for online texture characterisation in steel production facilities and further optimise the process.

The measurement of remanence with an angle to the rolling direction in the rolling plane has been identified as the optimum experimental method to measure the texture in steels. This led to future modelling and EM sensor measurement research work, followed up after the project period.



Above: Measured texture component for different steel samples.

# Introducing high-temperature hyperspectral electronics to the Foundation Industries

**Professor Jon Willmott, University of Sheffield**

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**In collaboration with Tata Steel**

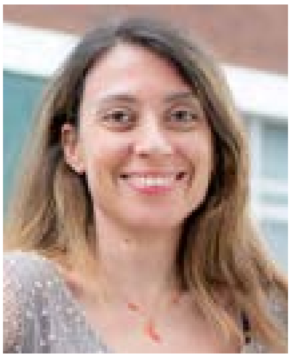
Hyperspectral metrology utilising a visible-range hyperspectral imaging system has been verified through testing with high-temperature hydrocarbon flames. Gas-phase flames were imaged, and the spectral emission of methane-air flames comprehensively investigated. The results demonstrated that the newly developed system can capture the gas-phase flames precisely and that the high spatial resolution targets the combustion reaction zone. The ratio of intermediate products with characteristic bonding (C2 and CH) may be determined, thereby monitoring the mixture of fuel and oxygen and enabling improvements in energy efficiency.

In addition, a mid-wavelength, infrared (MWIR) spectrometer was successfully built with low-cost, commercial off the shelf parts. The optical design software, Zemax suggested that a spectral range of 3 – 4 µm with resolution of <20 nm / pixel was achievable with the current design. The MWIR detector was tested with a blackbody furnace, demonstrating the circuit worked correctly and that the detector had adequate sensitivity to temperatures that radiate energy at these wavelengths. Although proof of concept for monitoring of $NO_x$ emissions was broadly shown, the arrangement of the optics required further improvement due to difficulty in alignment, necessitating a higher tolerance optic block.

Our spin-out company, PyrOptik Instruments Limited, will look to exploit the outputs of this work commercially, under university licence, offering services to the Foundation Industries, particularly for the energy generation.

Above: Ultra low cost mid-wave infrared spectrometer.

# Data-driven optimisation framework for assessing energy and emission saving potentials in Foundation Industries



**Dr Alessandra Parisio, University of Manchester**

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**In collaboration with Palm Paper**

This project focussed on the assessment of prospective energy and cost savings associated with Foundation Industries. A case study of Palm Paper was considered but the underlying concepts transcend this specific application. Palm Paper is a paper production company which produces newsprints and news paper grades from completely recycled materials, and who rely on natural gas and electricity for their energy sources.

The project took place over 3 phases:

(1) **Building Datasets**: This phase entailed the development of appropriate experiments required to capture dynamic or static properties of the paper production process. It encompasses data collection, processing and analysis which forms the basis of the system modelling.

(2) **Identification of Benchmark Representative Production Activities**: This task required the identification of manipulated, controlled and measured variables based on available data and included interactions between the boilers, combined heat and power (CHP) systems, paper separation plants, and pulping and de-inking station.

(3) **Data-driven modelling**: Each sub process was modelled and subsequently combined to represent the whole plant. Both static and dynamic models were considered depending on their suitability for predicting process outputs.

(4) **Optimisation**: The impact of this project is specifically embodied in the optimisation phase. A potential reduction in the gas and electricity consumed for paper production is projected with a Model Predictive Controller implemented. This translated to eventual processing cost reduction and energy savings, which are expected to range between 10% and 50%.

The research identified suitable process models describing subunits of a paper production plant for the purpose of variable predictions and energy optimisation. Models were developed which captured static and dynamic behaviours of the plant and results are being compiled for a more detailed journal publication.

# Physics-informed digital twins for industrial heating processes (twin4heat)

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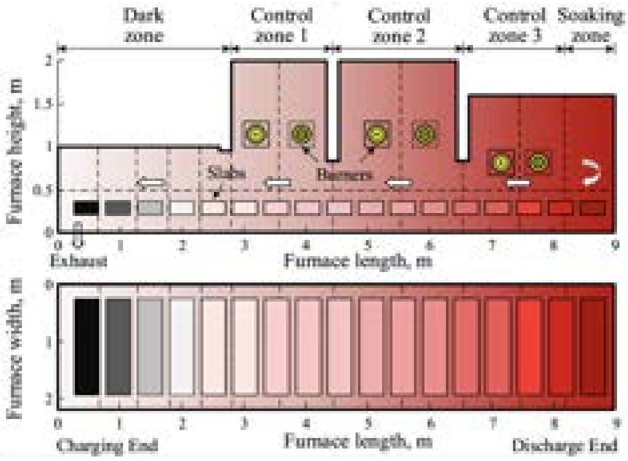
**In collaboration with VESUVIUS and SWERIM**

Twin4heat's ambition was to accelerate the UK's Net-Zero trajectory through next generation industrial heating processes using artificial intelligence to break through the predictive capability bottleneck of most surrogate models due to time consuming data acquisition in thermal analysis, design and optimisation. It aimed to tackle the challenge of automatic, fast, and frequent temperature prediction and setpoint estimation tasks (the most wide-spread tasks in the intelligent industrial heating process) by embedding physics knowledge of heating processes into Artificial Neural Networks.

The project studied the problem of predicting temperatures within a digital twin model of an industrial heating system, such as the reheating furnaces, via modelling the underlying physical phenomenon of radiative heat transfer. The first contribution is to cast the prediction problem as a regression task to employ Machine Learning (ML) based methods. Then, physics-based regularisation terms derived from the classical Hottel's zone method are proposed for equipping a neural network with better generalisability. Evaluating the proposed approach against a range of ML baselines using simulated data from a real-world furnace showcased the exceptional capabilities of neural networks to leverage the benefits of physical knowledge. Twin4Heat's ground-breaking methodology holds tremendous potential for transforming industrial heating processes, enabling substantial advancements in energy efficiency, emissions reduction, sustainability, and profitability within the Foundation Industries.




Above: Illustration of a real-world furnace, and its subdivision as different zones.

# High temperature optical fibre coatings for next generation gas emission monitoring (HiT OFCs)

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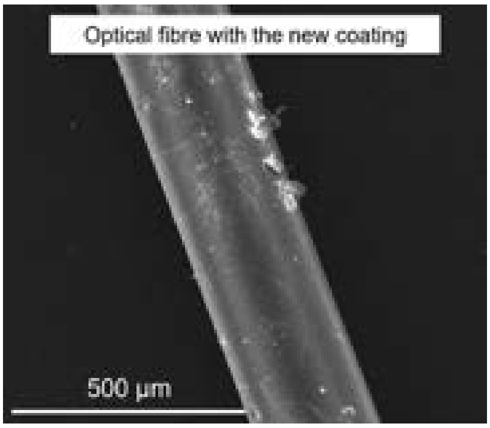
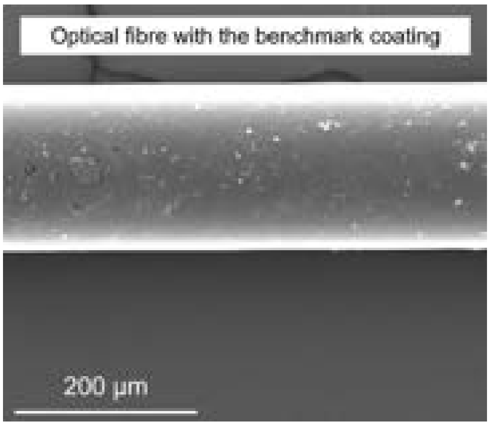
**Ronak.Janani@shu.ac.uk**

**In collaboration with the University of Southampton, IS-Instruments, University of Newcastle, Glass Technology Services, Breedon and Wienerberger**

Real-time gas emission monitoring with high sensitivity (ppm) is a prerequisite to the step-changes necessary in UK Foundation Industries for reductions in environmental emissions and energy consumption to achieve net zero. Current emissions monitoring techniques impose limitations to efficiency, detection limits and detectable gaseous species. We have been developing a new gas-Raman instrument capable of near-to-real-time, reliable detection of a wide range of gaseous species of key interest to FIs ($H_2O$, CO, $CO_2$, NOx, $SO_2$, HCl, HF, $NH_3$, VOCs). This device can be implemented across all FIs and other sectors requiring real-time emission monitoring. By enabling real-time monitoring, the collected data can be fed back into process control, to continuously optimise process parameters, optimising fuel use and minimising $CO_2$ emissions. Efficient environmental sensors could save ≈0.26 million TJ/year of energy across all energy-consuming sectors which is equivalent to ≈15 Mt of $CO_2$ globally.

This project aimed to increase the TRL of the developing gas-Raman technology by examining and ranking a number of optical fibre coatings based on their high temperature (≥ 200°C) performance, ease of handling / application, chemical stability and flow behaviour. Based on literature review, four UV-curable acrylate coatings were selected as potential candidates. The flow behaviour and the thermal performance of all four coatings were characterised and compared against the benchmark coating to select the most suitable for the present application of interest. Our findings have enabled pilot manufacturing of hollow-core fibres for high temperature applications, a key step towards developing a heat-resistant hollow core optical fibre as a key component for the gas-Raman instrument.




Above: Electron microscopy images of optical fibres coated with the benchmark coating and the new high temperature coating.

# Accurate emissivity characterisation of metals from near infrared (NIR) to long wave infrared (LWIR)

**Dr Matthew Hobbs, The University of Sheffield**

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**In collaboration with PyrOptik Instruments Limited**

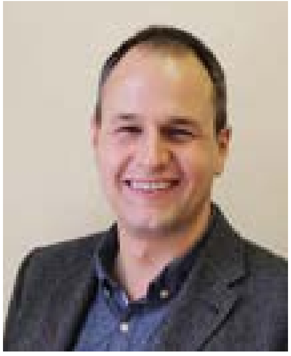
Emissivity is an often-overlooked characteristic of a material; it represents a material's efficiency to radiate thermal energy. In order to accurately measure the temperature of a process using infrared radiation thermometry, the emissivity of the material needs to be known. Without an accurate temperature measurement, the process cannot be optimised, leading to compromised material quality and increased carbon emissions.

In this work, we have developed an optical technique for the accurate measurement of a material's emissivity as a function of wavelength and temperature. The technique enables the emissivity of the material to be quantified from the near infrared (NIR) through to the long-wave infrared (LWIR); this was demonstrated within this project for a stainless steel 304 (SS304) sample. Whilst primarily developed for the accurate quantification of emissivity within the metals industry, it can be applied to other sectors within the Foundation Industries.

This emissivity measurement data can be incorporated into infrared radiation thermometers to enable a more accurate measure of manufacturing process temperature. This data can also be incorporated into heat transfer models and for the optimisation of waste heat recovery. Given the significant amount of energy used to generate the temperatures required within the Foundation Industries, even a small improvement in the temperature measurement accuracy due to better knowledge of emissivity will result in optimised processes. Ultimately, this will lead to reduced energy usage, lower carbon emissions, and improved material quality, resulting in greater profitability, within the Foundation Industries.

Above: Dual radiometer setup with split-tube furnace.

# Sustainable advanced manufacturing via machine learning-assisted exploitation of sensing and data infrastructure



**Dr Iñaki Esnaola, University of Sheffield**

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**In collaboration with Robinson Brothers**

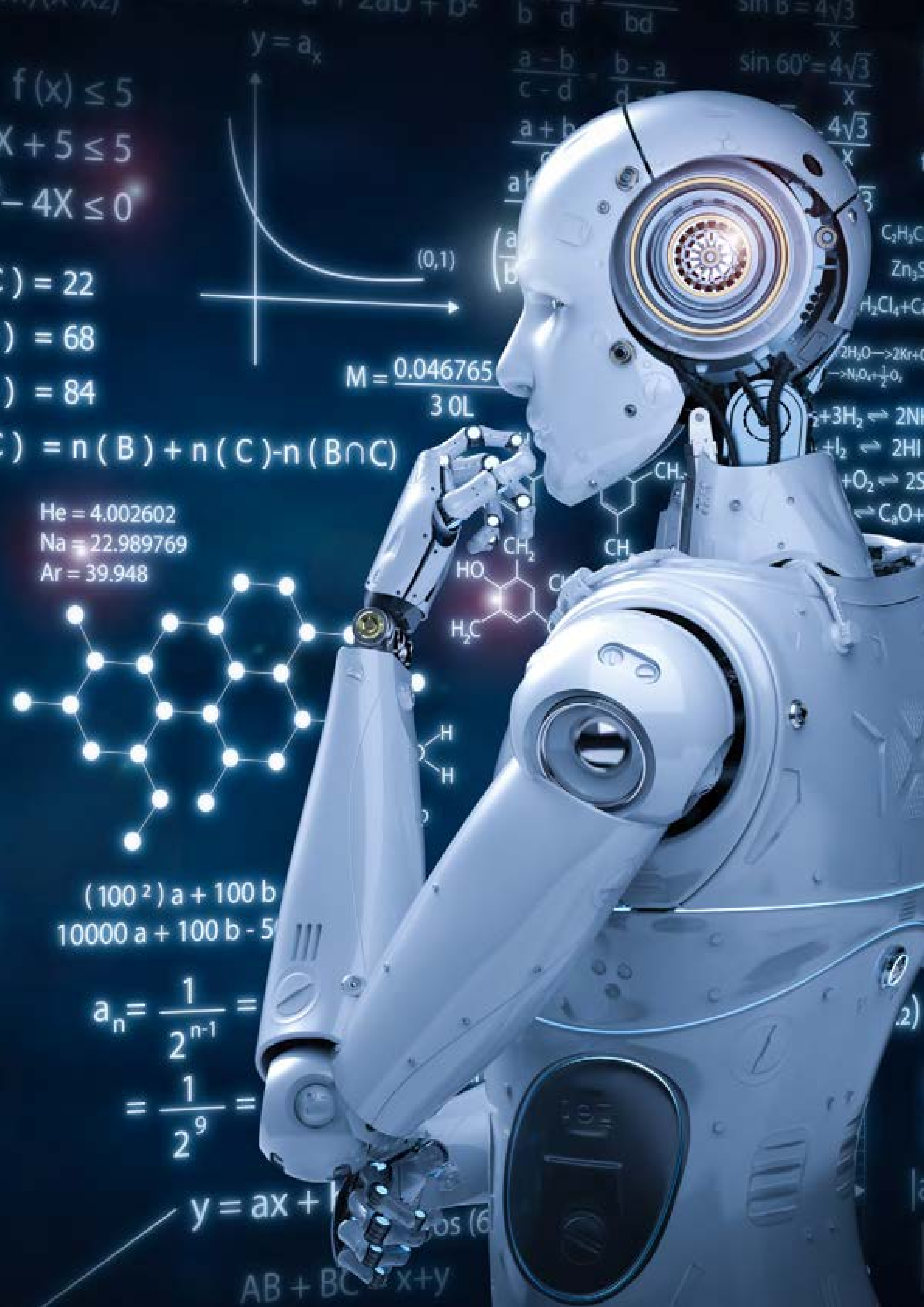
Machine learning (ML) and data science underpin research disciplines that are prominent in numerous manufacturing sectors, and are already achieving measurable impacts in high value, low volume sector such as aerospace and automotive. The applications supported through research in ML and data science are typically around process modelling, monitoring, optimisation, control and decision making.

This project aimed to develop integral data acquisition and analytics frameworks that leverage expert process knowledge with ML techniques to generate informed data infrastructure design guidelines that will accelerate uptake of ML in the Foundation Industries.

This project demonstrated that regardless of the amount of data that is captured, data science and ML tools can help improve the analysis and optimisation of manufacturing processes within Foundation Industries. While traditionally manufacturing within these sectors tend to operate in data-scarce regimes, data driven approaches that leverage first-principles understanding of the physical processes can enhance the analytical approach.

The project has proposed a mathematically rigorous quantitative framework that enables stakeholders to leverage their data with the following tools and methods:

- A stochastic model that can adapt to different levels of uncertainty, complexity, and data availability regimes.
- A data acquisition framework that also produces information metrics describing the evidence captured by different data sources about the parameters determining process performance.
- An ML framework that adapts to the amount of available data and incorporates the evidence provided by the information metrics into the task.



y = a
f(x) ≤ 5
X + 5 ≤ 5
– 4X ≤ 0
(0,1)
) = 22
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3 0L
) = n ( B ) + n ( C )-n ( B∩C)
He = 4.002602
Na = 22.989769
Ar = 39.948
sin 60° = 4√3
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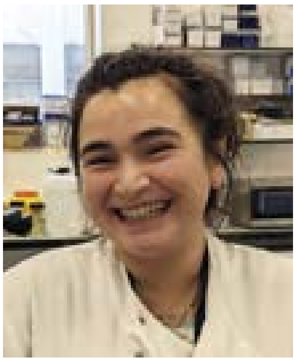
# Early Career Researcher-led projects.

# Developing biocomposite materials as low-carbon alternatives to ceramic tiles

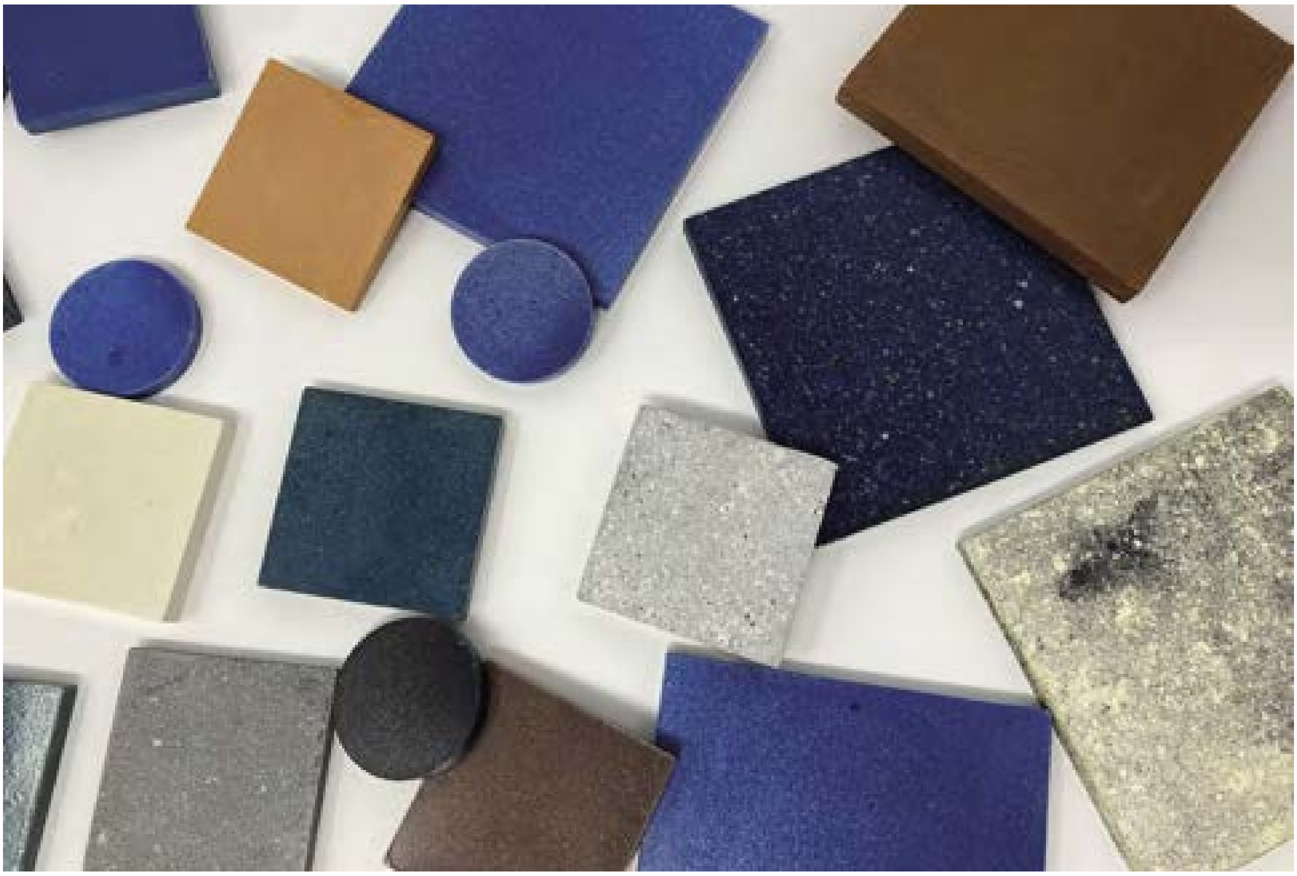


**Dr Alessia Andrews, University of Manchester**

**alessia.andrews@manchester.ac.uk**

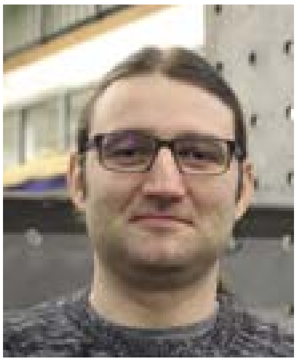
**In collaboration with Deakinbio, UK (Dr. Aled Roberts - aled.roberts@manchester.ac.uk)**

The project focussed on formulation and process optimisation to develop and improve the performance of low-carbon, bio-based alternative to ceramic tiles. Optimised tiles displayed improved mechanical properties giving flexural strength up to 25 MPa, in excess of our initial target of 12 MPa. The methodology concentrated on an iterative statistical Design of Experiments (DoE) which allowed quick and efficient exploration of the complex parameter space and screening of a wide range of additives (27 in total) at various concentrations. Our products now exceed minimum performance requirements in terms of flexural strength (12 MPa) as outlined in active standard EN14411 which has enabled Deakinbio to switch from R&D to small-scale commercial production – a significant milestone for an early-stage startup.



Above: Bio-based tiles.

# Element-based mapping of waste and by-product material flows – a transformational enabler for industrial symbiosis



**Dr Alastair Marsh and Dr Michal Drewniok, University of Leeds**

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**In collaboration with Tarmac Cement, Glass Futures, Wienerberger UK, CELSA Steel UK**

The Foundation Industries are keen to reduce the amount of raw materials they consume, and maximise the value of the by-products they generate. However, they lack integrated information about the volumes, chemical composition and end use of 'waste' which presents a barrier to industrial symbiosis. We have therefore developed a simplified model to map material inputs and outputs for the cement, ceramics, steel and glass sectors in the UK by focussing on the flows of key chemical elements relevant to each sector and combining compositional and mass flow data for each material stream. Using Sankey diagrams to visualise these elemental flows, we identified 8 untapped potential opportunities for industrial symbiosis between the ceramics, cement, steel and glass sectors such the use of blast furnace slag (from steel production) as a replacement for brick clay (for use in the ceramics sector) and cement kiln dust (from cement production) as a replacement for limestone (for use in the steel sector). This element flow mapping approach may be applied to other industrial sectors and also at an individual plant level.

# New Metrology for Hydrogen Flame Imaging

**Dr Yufeng Lai, University of Sheffield**

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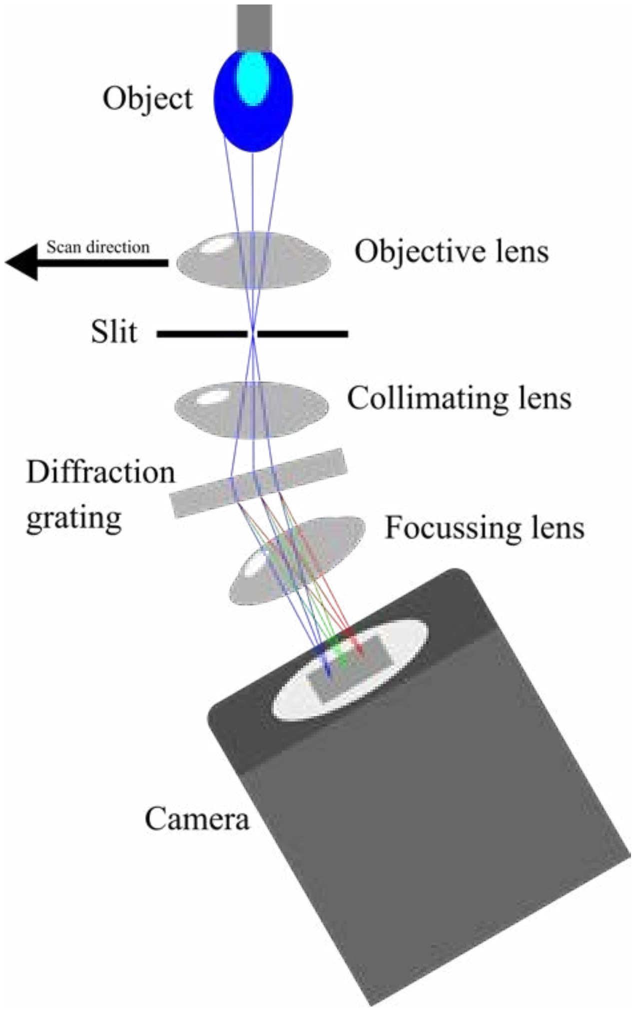
**In collaboration with PyrOptik Instruments Limited**

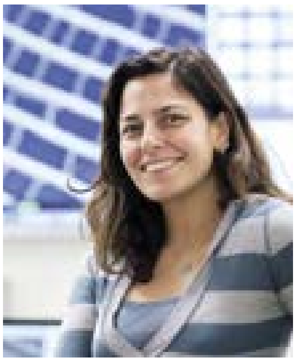
Hydrogen is an important source of energy, but visualising and measuring the temperature of its flames is a significant challenge to ensure its safe and efficient use and to understand the combustion process. The low intensity of hydrogen flame radiation in the visible and near-infrared regions of the electromagnetic spectrum make it difficult to visualise, while the gas-phase temperatures are challenging to measure accurately.

The project devised new metrology for hydrogen flame imaging and temperature measurement, utilising a near infrared hyperspectral imaging system. Three water vibrational-rotational bands useful for hydrogen flame visualisation were also identified and were utilised to form an artificial colour map with their integrated intensity used to build an empirical equation. The project, therefore, has accelerated progress in hydrogen fuel development and will enhance energy efficiency by providing accurate temperature measurements and facilitating the visualisation of hydrogen flames for the Foundation Industries. PyrOptik Instruments Limited plan to commercially exploit these results as the use of hydrogen becomes more prevalent in the transition to net zero.




Above: Figure shows the NIR hyperspectral imaging system under development.

# Circularising the Pressure Moulding of Ceramics



**Dr Ahu Gumrah Dumanli-Parry, University of Manchester**

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**In collaboration with PCL Ceramics and Dr. Ozge Akbulut, Sabancı University, Istanbul**

In this project, we showcased an innovative way of processing ceramics in the dough form that is ideal for pressure-moulding (e.g., ram pressing and injection moulding) at room temperature with a minimum required pressure. This involved the incorporation of a single copolymer additive at a minimum amount to induce polymer bridging to obtain a self-standing, malleable dough structure. The stamping experiment showed that the pattern on the stamp is flawlessly copied onto the ceramic dough when the stamp is lifted. The dough formulation required little pressure, making it cost-effective and energy efficient. Additionally, a different non-malleable, yet injectable, formulation was developed for injection moulding that had lower viscosity.

The resulting density of the sintered materials was measured to be 96.7% of the theoretical density, indicating a high level of densification and minimal porosity. Flexural strength of 172 MPa was obtained, using a three-point bending standard C1161-13.

This new processing method has significant potential to facilitate the production of intricate and complex shapes without compromising the mechanical integrity of the materials. It offers several advantages over traditional casting methods, including increased productivity as well as reductions in the equipment cost, amount of chemicals, and $CO_2$ emissions. The successful demonstration of the two moulding ability will facilitate development of advanced ceramics for tailored applications according to industry needs. An environmental impact assessment study was also carried out to provide a valuable insight, primarily for our industrial partner, which can be applied to different product development stages in the ceramics industry. Our analysis clearly indicates that our approach can contribute to the Ceramics Innovation Network's carbon-net-zero aims, demonstrating the potential for significant positive impact.

Below: Pressure moulded ceramic samples.

# Low-temperature densification of α-$Al_2O_3$ through a modified cold-sintering process

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**In collaboration with Johnson Matthey**

α-$Al_2O_3$ is a technical/advanced ceramic used in applications such as electrical insulation, wear, and corrosion resistance, with approximately 120,000 metric tonnes manufactured per year worldwide. Conventional processing of α-$Al_2O_3$ ceramics requires significant effort in optimising physical powder characteristics through reduction in particle size, followed by sintering at ~1600 °C to achieve the required densification. In this project, the technique of cold-sintering was considered as an aid to densification, the aim being to reduce significantly the sintering temperature thereby offering significant energy savings in processing and also decreasing the intrinsic costs of infrastructure and capital equipment (furnace and element technology is far less stringent when densification can be achieved at ≤1400 °C).

Pseudo-boehmite (Al(O)(OH)n) is a low cost raw material used in the fabrication of alumina powders. It decomposes on heating to form α alumina at >1100 °C after passing through a complex sequence of phase transitions. It can be functionalised as a prelude to cold sintering using ~1 molar acetic acid to form a surface coating of acetate-alumoxane powder. The functionalised powder may then be cold sintered to near 100 % dense if required but in this study the pseudo-boehmite was mixed with α-$Al_2O_3$ and aluminium nitrate to form cold sintered dense composites which could subsequently be heat treated to form α-$Al_2O_3$ pellets. A range of pressure, cold sintering temperatures and boehmite/ α-$Al_2O_3$/aluminium nitrate ratios were studied and the phase assemblage and densification investigated.

Although fully dense α-$Al_2O_3$ pellets were not achieved at 1200 °C, large areas of the pellets had densified with evidence of 120° triple junctions in parts of the ceramic. The absence of full densification suggests that better mixing may be required during the processing sets to ensure a homogenous distribution of the starting powders and potentially higher temperatures (even 1400 °C would still offer a significant energy saving and commercial advantage in capital equipment and infrastructure). This work has been extended through a further Early Career Researcher (Beatriz Almeida) supported by the European Ceramic Society and has formed part of an Engineering and Physical Sciences Council grant submission. A comprehensive publication of the data is planned.

# Improving Surface Interactions of Waste Plastics as Grain Substitutes Within Concrete

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**In collaboration with AMCRETE**

The cement industry is one of the biggest $CO_2$ emitters on the planet and concurrently, we are facing a global crisis in plastic waste and how to repurpose, reuse or recycle it rather than disposing of it in landfill/incineration. The scope of this project was to allow concrete to be 'dematerialised' by using less raw material, reduce costs through the use of 'zero/negative-value' polymer waste streams in concrete whilst also improving mechanical properties of the final polymer-concrete composite.

Through collaboration across academic sectors, we aimed to tackle both described issues through the use and optimisation of polymeric waste streams (specifically polypropylene, PP) as organic binders for high performance concrete composites. Previously, the inclusion of waste polymers in concrete has been found to degrade the mechanical properties of concrete compared to standard concrete. We therefore tackled these limitations by applying a 'bottom-up' approach to aggregate-inorganic oxide surface interactions and material performance. Specifically, this research studied the chemistry of interactions between inorganic oxides and cement with functional groups introduced into polymeric materials to allow correlation and insight on these interactions and optimise the final polymer-concrete composite. We found via Fourier-transform infra-red analysis (FTIR) we were able to observe how our proposed functional groups effected bond formation during the pozzolanic reaction of cement curing. We were then able to functionalise model polymers with these groups and then formulate concrete with the functionalised polymer. Concrete made in this way was found to have lower strength when compared to control samples made without polymer, however, the strength was still acceptable for building materials. Concrete formulated with pozzolanic active polymer was also found to be more workable and require less superplasticiser, typically the most expensive ingredient of concrete.

# Sustainable asphalt pavements with recycled concrete aggregate and waste glass

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**In collaboration with Total Reclaims Demolition Ltd**

Asphalt serves as the primary surfacing material for the road infrastructure in the UK, comprising mineral aggregates and bitumen. However, Foundation Industries in the UK generate a substantial amount of waste concrete and glass, which presents an opportunity to replace the limited natural aggregates. This project focused on integrating recycled concrete aggregate (RCA) and recycled glass cullet (RGC) into the production of sustainable and high-performance asphalt pavements.

One of the main challenges associated with using recycled aggregate materials is their lower mechanical strength and weaker bonding with bituminous mortar. To address these issues, this project employed two surface treatment methods for RCA: polymer impregnation using polyvinyl alcohol (PVA) and pozzolan slurry soaking, using either fly ash and silica fume (FA&SF), fly ash and cement (FA&C) or fumed nanosilica (NSF).

The density, water absorption, porosity and surface morphology of RCA were comprehensively assessed before and after the surface treatment. The results show that both surface treatment methods reduce the water absorption and porosity, as well as enhance the microstructure and improve the surface homogeneity of RCA.

Overall, the utilisation of RCA (and RGC) derived from the Foundation Industries holds great promise as a viable alternative to the excessive use of natural aggregates in the construction of future high-quality and sustainable asphalt pavements. Based on the findings in this project, the PI has secured another grant entitled: "Enabling Construction Material Circularity in the Transport Infrastructure Sector" awarded by Innovation Launchpad Network+ EPSRC in collaboration with Connected Places Catapult and peer reviewed papers are being published to disseminate the results.


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