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Magnesia-bearing Construction Materials for Future Energy Infrastructure: Status Quo and Next Steps

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ABSTRACT

Our infrastructure faces unprecedented challenges in addressing a low carbon future with limited natural resources, expanding population, increased pollution and climatic uncertainties. Current construction materials, which mainly revolve around Portland cement formulations, have many drawbacks and are unable to meet the stringent sustainability and long-term durability demands. Addressing anticipated challenges will require a fundamental revaluation of the most appropriate construction materials for future infrastructure. Adaptation and innovations must therefore play a vital role in making future construction materials more resilient and robust. Project MagMats: Magnesia-bearing construction materials for future energy infrastructure, now in its third year, has been developing a world leading and long lasting partnership between academics in the UK and China with unique expertise in magnesia-bearing materials. This paper presents an overview of the range of MgO-bearing construction materials that are being developed with enhanced performance for different energy infrastructure applications. These include: MgO as an expansive additive to compensate for different types of shrinkages in large mass concrete dam construction and gas/oil wells, MgO in alkali activated cements for enhanced resistance to chloride and carbonation induced corrosion, magnesium phosphate cements for compatibility with nuclear wastes, and MgO in carbonated products for low carbon cements. The research gaps and opportunities have been identified and a suite of MgO-bearing construction materials are being developed and formulated, leading to the development of deeper understanding and promoting real-world applications. In addition, the potential of utilising alternative and waste magnesium sources for producing MgOs are also being developed and advanced as a means of addressing the sustainability issues associated with the calcination of magnesite. The sharing of these findings will advance our understanding of MgO-bearing materials, roadmap future research agendas and identify the ideal applications in our future energy infrastructure where most performance impact and sustainability benefits can be achieved.

1. INTRODUCTION

By 2020, both the UK and China plan to produce 15% of their primary energy mix from renewables. Nuclear and wind power have been proposed as clean energy sources for both China and the UK, while hydropower will also be a major player in China. The pressing demand for low-carbon energy is intrinsically linked to new infrastructure-related material challenges. including (i) deeper offshore marine environments for wind power generation, (ii) deeper and more complex underground wellbore systems for new oil & gas explorations, (iii) more robust containment and shielding structures and radioactive waste encapsulation for nuclear power plants and (iv) larger dam structures for hydropower generation. Portland cement (PC), currently the backbone of most construction, is the most widely used cement and its technical and durability credentials are unparalleled. However, it is responsible for significant anthropogenic CO_2 emissions and huge negative environmental impacts [1]. It also has specific technical drawbacks and as a result will be unable to meet many of the stringent technical performance and long-term durability demands. The main issues include thermal and long term shrinkage, susceptibility to chloride-and carbonation- induced corrosions, incompatibility with certain nuclear wastes and encapsulation environments and rheology-related problems under extreme temperature and pressure conditions.

In this context, the UK/China collaborative project MagMats: Magnesia-bearing Construction Materials for Future Energy Infrastructure which focuses on the development of MgO-bearing construction materials was launched in 2015. The project is a global collaboration including partners also from Brazil, Canada and Singapore. This collaboration augments the significant research efforts which have already been carried out in magnesia-bearing infrastructure materials [2,3]. This paper presents an overview of the various novel and advanced MgO-bearing construction materials being developed in MagMats. It has identified the research gaps and potential opportunities for advancing the proposed materials and formulations, leading to the development of deeper understanding and promoting their real-world applications.

2. MAGMATS: STATUS QUO & NEXT STEPS

The proposed programme of work has been divided into five work packages (WPs), designated to address five major research areas shown in Fig. 1. An overview on the status quo of each WP is presented and addressing the research gaps is planned for the foreseeable future.

2.1. MgO expansive cement

The team's research identified that the hydration and expansion properties of MgO are designable with adjustment of their microstructure through changes in calcining parameters during the manufacturing process and raw material sources, offering compensation not only for thermal, but also autogenous and drying shrinkages, significantly reducing the cracking potential [4,5]. This would enable more accurate and adaptable design of MgO as an expansive additive to address more complex and extreme shrinkage scenarios as would be expected in the super-large dams [6], oil/gas wells and nuclear shielding structures. Currently, a commercial manufacturing line for MgO expansive additive has been established, which produces MgO expansive additives at a large industrial scale (production capacity: 1000 t/d) with stable quality. The relevant standards or specifications of MgO-based expansive additives are being drafted in China. However, various challenges remain including: (i) precise control of the expansion process of concrete containing the appropriate type and addition content of MgO; (ii) evaluation of MgO concrete soundness with supplementary cementitious materials (SCMs); and (iii) extended applications in energy infrastructures, e.g. reinforced concrete foundation for wind turbines and cement sheath for oil/gas wellbore, where the service conditions are far more complex, e.g. elevated temperatures/pressures or in seawater environments at lower temperatures.

2.2. MgO-modified alkali-activated cements (AAC)

The application of AAC is hindered by excessive shrinkage and carbonation, a lack of appropriate advanced chemical admixtures to achieve an appropriate workability and the difficulty in handling and curing. A major recent advance by the research team has been the demonstration of the significant performance enhancement obtained by incorporating reactive MgO in AAC [7–9]. Reactive MgO reacts with Al-containing minerals to form extensive quantities of hydrotalcite-like phases (Ht), leading to strength improvement and shrinkage reduction and potentially better durability against chloride and CO_2 attack. However, the development of MgO-AAC is still in its infancy leaving many questions unanswered. To name a few, these are: (i) CO_2 and chloride resistance of MgO-AAC materials needs to be confirmed by experimental results; (ii) microwave curing could serve as a faster

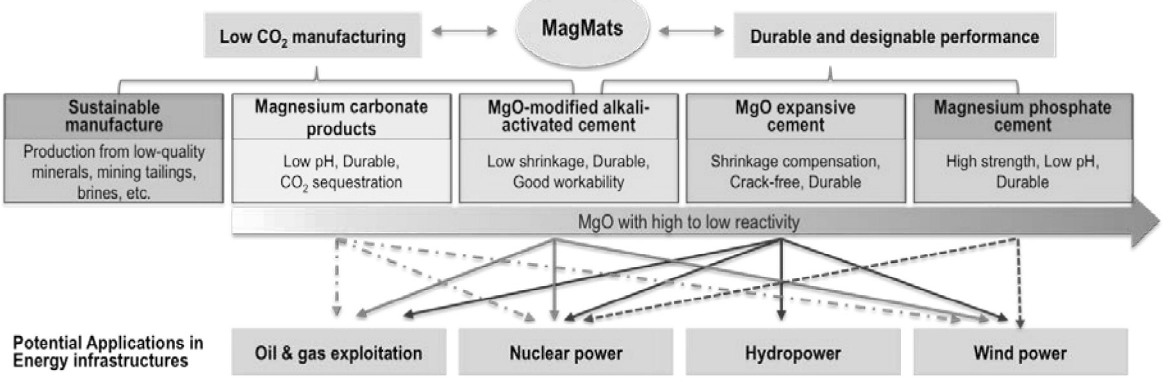

Figure 1. *MagMats project overview*

and more sustainable method for AAC manufacturing [10], yet its effect on the MgO-AAC blend is unclear; and (iii) use of Al-containing waste (e.g., red mud) in MgO-AAC blends would promote the formation of Ht, warranting further investigation.

2.3. Magnesium phosphate cements (MPCs)

MPCs have rapid and high strength development, extremely high bond strength and low shrinkage compared to PC, and have hence been used in rapid repair applications [11,12]. Their relatively low pH, low permeability, dense microstructure and high durability have fueled research into their use in long-term nuclear waste encapsulation, offshore construction and structures for wind power or oil & gas applications [12,13]. The team has found that through the careful control of the temperature during curing, retarding components can be used to create a mix with a high proportion of aggregates, showing acceptable working times and flow properties, while maintaining a rapid strength gain and reducing costs [14]. The effects of MPC mix compositions and curing temperature on its rheological, mechanical, durability properties and microstructure have been thoroughly investigated by the team [15]. In addition, the MPC mixes (including pure MPC, GGBS-MPC and PFA-MPC blends), demonstrated superb capability for immobilising Cs (>99.5% immobilisation efficiency) at all curing ages investigated, which is twice the efficiency achieved by the traditional PC and PC-GGBS mixes. These modified MPC show great potential in nuclear waste encapsulation although many challenges exist including: (i) detailed immobilisation mechanisms of MPC towards nuclear wastes are not fully understood and are important for predicting the long-term performance of encapsulation systems and (ii) deterioration mechanisms of MPC under various aggressive marine environments such as carbonation, sulfate and chloride attack require detailed investigations.

2.4. Magnesium carbonate products

The research team has conducted extensive research on MgO in a range of carbonate products [16–20]. The work involved the accelerated carbonation of MgO in Ca-rich blends which led to the formation of a different range of carbonation products, namely magnesian calcite which exhibits a much higher binding ability than calcite [16–18]. These Mg-bearing carbonate products are chemically more stable and offer far more resistance to aggressive marine environments than portlandite or calcite. In addition, the hydrated magnesium carbonates (HMCs), e.g. nesquehonite and hydromagnesite, which formed due to the carbonation of MgO had well ramified networks of massive dense different morphology crystals that resulted in a very effective binding ability and significant strength development of carbonated MgO porous blocks [19] and concretes [20]. Cost-effective measures to improve the sustainability of these carbonated MgO systems include the use of SCMs, e.g. PFA, and other carbonation-reactive materials such as steel slag. However, the long-term durability of these carbonate systems remains unclear. First, the phase stability of the various HMCs at different temperatures and humidity levels needs further research. The carbonation rate and acid resistance are highly dependent on the mix compositions and the permeability of the final product and therefore needs validation and optimisation through experiments. Finally, the feasibility study on the scale-up manufacturing and application of the various Mg-carbonate systems from the perspective of sustainability is needed.

2.5. Sustainable manufacturing of MgO

The team's current research and commercial attempts to reduce MgO production emissions include the use of low-grade magnesite, dolomite and Mg-mineral wastes [21] and through CO_2 sequestration in seawater or reject brines [22]. High purity (MgO content>93%) and high reactivity (SSA=78.8 m^2/g) MgO has been obtained from a real reject brine that contains various impurities. However, the effect of different impurities on the characteristics of the MgOs is yet to be quantified. Further research will thoroughly characterise the MgOs produced from the various waste source and evaluate their performance in the abovementioned various MgO-bearing materials. The ultimate goal is to produce MgO samples with designable properties so that for a given MgO-bearing cementitious material its maximum potential will be explored.

3. CONCLUSIONS

Given the expected construction explosion, complexity and volume of concrete that will be used in future energy infrastructures, the proposed use of MgO-bearing materials is likely to have a major impact in providing the safe and reliable delivery of our future energy infrastructures and will have a much wider impact on all aspects of future construction activities. Project MagMats has been conducting focused research on targeted areas and applications. These include: MgO as an expansive additive in large dams and oil/gas wells; MgO in AAC for improved chemical & CO_2 resistance; magnesium phosphate cements for encapsulation of nuclear wastes; MgO in carbonated products for enhanced sustainability and durability. In addition, the potential of utilising alternative and waste magnesium sources for producing MgOs has been advanced. Although Project MagMats is making significant advances in our global understanding and in the implementation of MgO-bearing infrastructure materials, there are more challenges that facing us moving forward. New research topics targeting key problems were identified to further advance our knowledge and promote real applications of the proposed materials in future challenging energy infrastructure. It is expected that future research will fill gaps we identified and fulfill the commercial needs in our future energy infrastructures where most performance impact and sustainability benefits can be achieved.

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