Reutilising waste clays from tunnelling operations as a cement replacement material in concrete – An innovative circular approach

Reutilising waste clays from tunnelling operations as a cement replacement material in concrete - An innovative circular approach

Fragkoulis Kanavaris
ARUP, London, UK
Daisy Ronn
ARUP, Toronto, Canada
Athina Papakosta, Apostolos Tsoumelekas
SCSJV, London, UK

ABSTRACT
As part of a major tunnelling project in the United Kingdom, significant volumes of London Clay will be excavated in the wider London area in the UK. The excavated material would normally be treated as waste, sent to landfill or incorporated into landscaping. Instead, a method is developed to turn the excavated London Clay spoil into a construction resource such as supplementary cementitious material (SCM) and / or lightweight aggregate. This paper reports the developments within the Re-Purposed Excavated Arisings Loop (REAL) research project aiming to transform London Clay spoil into such construction resources. It encompasses investigations on the plastic, micro-structural and chemical properties of raw and calcined London Clays, as well as hardened concrete and mortar properties produced with those clays. The material characterisation results demonstrated that London Clay, in its calcined form, can be a suitable SCM for low/medium strength concrete. The REAL project aims at developing robust concrete mixes with compressive strengths of up to 40 or 50 MPa, and Portland cement replacement levels of up to 70%. Additionally, the possibility of producing expanded clay lightweight aggregate from excavated London Clay is also explored. Preliminary lab test results indicate material suitability for certain construction applications – an important step towards a circular economy approach for large construction projects. While this innovative approach has been developed as part of a major infrastructure project in the UK, it encompasses high potential to be extrapolated to other locations and similar projects, e.g., those in North America and Canada specifically or beyond.

1 INTRODUCTION

Due to population growth, rapid urbanization, and the climate crisis, the construction industry needs to reevaluate its traditional practices of sourcing and disposing of materials in a linear manner. It should adopt alternative techniques to meet the increasing demand for infrastructure in an environmentally sustainable way.

Concrete, being the most commonly used building material, requires exploration of new, accessible, and low-carbon alternatives for its key components, namely cement and aggregates. In Europe, the stock levels of the main substitutes for Portland cement, such as fly ash and ground granulated blast furnace slag (GGBS), are decreasing. This is due to the phasing out of the industries that produce them, namely coal and primary steelmaking, and the growing demand for concrete in new developments.

Managing waste and logistics in construction, especially in dense urban areas, is challenging in terms of execution, budgeting, and scheduling. There are also concerns about negative impacts on the environment and local surroundings. Tunnelling and deep excavations generate significant amounts of spoil that need to be transported and disposed of offsite, resulting in carbon emissions, air pollution, and costs. To address the issue of spoil disposal, the United Kingdom's Green Construction Board recently published "The Routemap for Zero Avoidable Waste in Construction" (TGB, 2021). This roadmap aims to reduce landfilling of soil by 75% by 2040 and achieve zero soil going to landfill by 2050. Efforts have been made to utilize such excavated materials in landscaping and as fill material in recent years. However, the potential to convert excavated spoil into a valuable construction resource like concrete has largely been overlooked thus far.

2 THE CASE OF “REAL” PROJECT AS PART OF HIGH SPEED 2 RAILWAY IN THE UK

2.1 Description

As part of a major railway project in the United Kingdom, namely High Speed 2 (HS2), large volumes of clay will be excavated (e.g., Fig. 1). HS2 will need to manage large amounts of excavation arisings, particularly in the greater London area. Extensive tunnelling will need to be undertaken underneath central London, producing high volumes of London clay spoil. This challenge is common among underground infrastructure works in urban areas and is typically addressed by transporting the excavated material, often over long distances, to disposal/landfill sites (Kanavaris, 2022; Papakosta et al. 2020).

London Clay is a geological formation abundant in the London Basin in the United Kingdom (2022), which has traditionally been exploited for brick manufacturing (Brunskill, 1997). Its clay mineralogy consists mainly of chlorite, kaolinite, illite, and montmorillonite. London Clay encompasses relatively low kaolinite contents (10-30%) (Kemp and Wagner, 2006), which is the primary indicator in terms of suitability of clay materials as supplementary cementitious materials in concrete (Scrivener et al. 2018). Despite this, it may still have potential to be used as a supplementary cementitious material (SCM) in its calcined form, or to be used to produce expanded clay aggregate. This section provides an overview of the main objectives and selected results of the REAL (Re-purposed Excavated Arisings Loop) project, which has explored and revealed this potential.

Figure 1. Photograph of a High Speed 2 construction site for a concrete shaft and collected excavated London Clay

2.2 Objectives

The overarching objective of the REAL project is to respond to the aforementioned challenges, through investigating the viability of re-purposing excavation arisings to produce constituent materials for use in concrete. Successful implementation and rollout of this more circular approach could result in minimised waste streams to landfill. This in turn would: avoid the environmental impacts and costs associated with transport and disposal; improve resource efficiency; reduce the need for imported materials; stimulate innovation in construction products; generate new skills and employment; and, help leave a positive legacy for the construction industry. The project is focused on repurposing London Clay, which is the most frequently encountered geological formation in Greater London. This includes most of the tunnelling and excavation arisings in HS2 London works. Two main material outputs were targeted by processing excavated London Clay spoil:

- Calcined clay, for use as supplementary cementitious material in concrete mixes
- Pelletised expanded clay to form light weight aggregates (LWA), for use in concrete mixes and/or as fill material.

To deliver these two targeted outputs, REAL is structured as a modular feasibility study, with every step of the process dependent on the outcomes of the previous stages.

The two key project phases are:

- Stage 1 – Proof of concept: Materials and concrete feasibility study
    - 1.a. Raw material screening: London Clay material characterization
    - 1.b. London Clay-derived SCM & LWA: Performance testing & concrete trials
- Stage 2 – On-site use and production: On-site production and use of the London Clay derivatives and trial in High Speed 2 construction works

With the project having been initiated in 2019, Phase 1.a has now been completed and Phase 1.b is to be completed imminently – this latter phase focuses on the development of project specific concrete mixes. Investigations have shown that it is possible to manufacture calcined clay and LWA from waste London Clay, however, it was found that manufacturing calcined London Clay is more resource efficient compared to manufacturing LWA, thus focus is given on calcined clay in this paper. Results on LWA from waste London Clay can be found in Papakosta et a. 2020. The underlying science developed in the REAL research project will enable establishing the first on-site industrial production and application of calcined clay in continental Europe. Establishing an on-site calcined clay facility, even looking into converting low grade clays in SCMs, is expected to reduce transport carbon and exploit the temporary electrical supply already in place for the TBM operations. Alternatively, the excavated clay can be treated and calcined in a near-by calcination facility. This paper presents selected results from the REAL project demonstrating the feasibility of utilizing excavation waste clays as supplementary cementitious material in concrete.

2.3 Experimental programme

The initial project phases primarily focused on examining the characteristics of London Clays in their original state and after being calcined, in order to evaluate their suitability as supplementary cementitious materials (SCMs) in concrete. Additional tests were conducted to determine if the excavated London Clays were suitable for producing lightweight aggregates (LWA). Table 1 provides a description of the testing program and the properties being investigated, which were carried out in specialized institutions and laboratories in Europe and the United Kingdom (Kanavaris and Papakosta 2022; Papakosta et al. 2020). The testing program is continuously updated as the project progresses and is soon to be enriched with further tests related to durability and material properties specific to the needs of HS2.

Various forms of raw London Clay were collected for the testing program, including as excavated, extracted from the tunnelling boring machine with and without conditioning foams, and with or without moisture and chemical stabilization agents (quicklime), under moist and dry conditions. More than ten different sources of clay were tested to explore the variation of London Clay across different locations in the Greater London area and at different extraction depths.

Following the characterization tests, preliminary tests and trial mixes were conducted on pastes, mortars, and concretes. The objectives were to assess the effects and feasibility of using calcined London Clay as an SCM in terms of fresh and hardened properties, determine the optimal content of calcined London Clay in blended cements, and investigate the incorporation of limestone to exploit potential synergies between Portland cement, calcined clay, and limestone. Initial compressive strength tests were carried out using mixes containing CEM I 42.5 N, calcined London Clay, and limestone in accordance with EN 206. Further mixes with calcined London Clay were developed in the laboratory considering three CEM I replacement levels (30, 50 and 70%), different w/b and cement contents. Finally, concrete mixes have been developed on site focusing on 50 and 70% of CEM I with calcined London Clay.

Table 1. Material testing and characterization considered as part of the REAL project

Testing type	Test	Pertinent to
Initial classification	Particle size distribution (PSD)	Raw London Clay
Initial classification	Atterberg limits	Raw London Clay
Microstructural	X-Ray Diffraction (XRD) & Rietveld analysis	Raw and Calcined London Clay
Microstructural	X-Ray Fluorescence (XRF)	Raw London Clay
Reactivity and Thermochemical	Calcination time and temperature verification	Calcined London Clay
Reactivity and Thermochemical	Thermogravimetric analysis (TGA)	Raw and Calcined London Clay
Reactivity and Thermochemical	Isothermal calorimetry and reactivity (R3)	Calcined London Clay
Pyrite/Sulfate content screening	X-Ray Diffraction (XRD)	Calcined London Clay
Production	Grinding and PSD	Calcined London Clay
Fresh concrete/mortar/paste properties	Slump/flow and mini slump/flow	Calcined London Clay
Fresh concrete/mortar properties	Bleeding, segregation and Visual Stability Index	Calcined London Clay
Hardened concrete properties	Compressive strength	Calcined London Clay

2.4 Selected results

When considering the suitability of clays as supplementary cementitious materials (SCMs) in general, certain crucial parameters are typically taken into account to assess the reactivity of the clay in its calcined form. Among these parameters, the kaolinite content in the clay plays a significant role: a low kaolinite content suggests low reactivity, while a high kaolinite content indicates high reactivity (Scrivener et al. 2018). Initial findings for kaolinite content based on TGA (Thermogravimetric Analysis) measurements on ten waste London Clay samples excavated from different depths indicated that the kaolinite content ranged from 18% to 22% (Kanavaris and Papakosta 2022; Papakosta et al. 2020), suggesting a relatively lower grade clay for concrete applications. However, further tests conducted on additional samples from different locations have indicated the possibility of slightly higher kaolinite contents, e.g., up to 30%, in other London Clays within the Greater London area.

Calcination of all samples was considered in different temperatures and durations whilst the most optimum calcination process was found to be heating to 800 °C for one hour. The reactivity of the calcined London Clay samples was reassessed through the R3 test and the kaolinite content was found to be vary approximately from 17-25% (Kanavaris and Papakosta 2022; Papakosta et al. 2020). Such kaolinite contents are normally considered low for the production of medium strength structural concrete (Joseph et al. 2023). The range of 28-day compressive strength achievable with the incorporation of calcined London Clay was therefore investigated.

The initial mixes with calcined London Clay investigated accounted for an LC3 formation in order to demonstrate the feasibility of calcined London Clay for producing structural concrete. Initial compressive strength results from mixes with 30% calcined London Clay, 15% limestone, 5% gypsum and 50% CEM I 42.5

N are shown in Figure 2 and that 28-day cube compressive strengths of 50 MPa can be achievable with the blends investigated and therefore, can potentially be used to produce structural concrete.

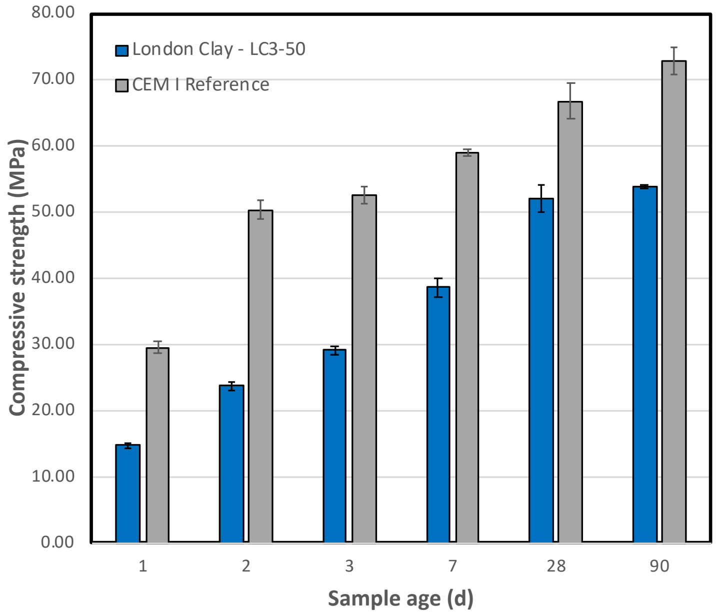

Figure 2. Compressive strength development of a mortar mix with 30% calcined London Clay (in-cluding 15% limestone and 5% gypsum) compared to a CEM I 42.5R mortar mix (Kanavaris and Papakosta, 2022)

Further characterization tests have been conducted and several mixes have been developed on site in order to assess the behavior of concrete mixes with calcined London Clay but without limestone. While the synergistic effects between limestone and calcined clay have been relatively well recognized, this part of the work focused on studying binary mixes with calcined London Clay for several key reasons. Firstly, it allows for maximizing the reuse of waste clay, thereby minimizing the amount of clay waste sent to landfills. Secondly, it aligns with UK standards that allow for the replacement of up to 55% of CEM I with calcined pozzolana, while ternary mixes incorporating limestone are not considered within these standards. Lastly, using a ternary binder introduces additional complexities for on-site production, including the sourcing, grinding, and blending of limestone. By focusing on binary (Portland cement + calcined London Clay) mixes, these complications can be reduced, simplifying the on-site production process. Examples from on-site production of concrete with calcined London Clay within the project can be seen in Figure 3.

(a) (b) (c)

Figure 3. (a) Calcined London Clay in its ground form prior to mixing on site, (b) slump tests on calcined London Clay concretes and (c) concrete cube for compression testing with 50% calcined London Clay.

Several mixes have been developed on site with calcined London Clay as part of the REAL project. Indicatively, compressive strength evolution of two key developed mixes is shown in Figure 4. The mixes encompassed 50% and 70% replacement of Portland cement (CEM I) with calcined London Clay, 307 and 260 kg/m^3 binder content and 0.6 w/b. It is demonstrated that achieving strengths needed for structural concrete with calcined London Clay it is feasible, since strengths of 48 MPa (7000 psi) and 35 MPa (5100 psi) were attained at 28 days after casting for 50 and 70% replacement of Portland cement, respectively. These results reveal the potential for utilizing “low grade” waste clays, e.g., clays with low reactivity, as a supplementary cementitious material in concrete which can contribute to reducing the embodied carbon of concrete used in underground structures significantly.

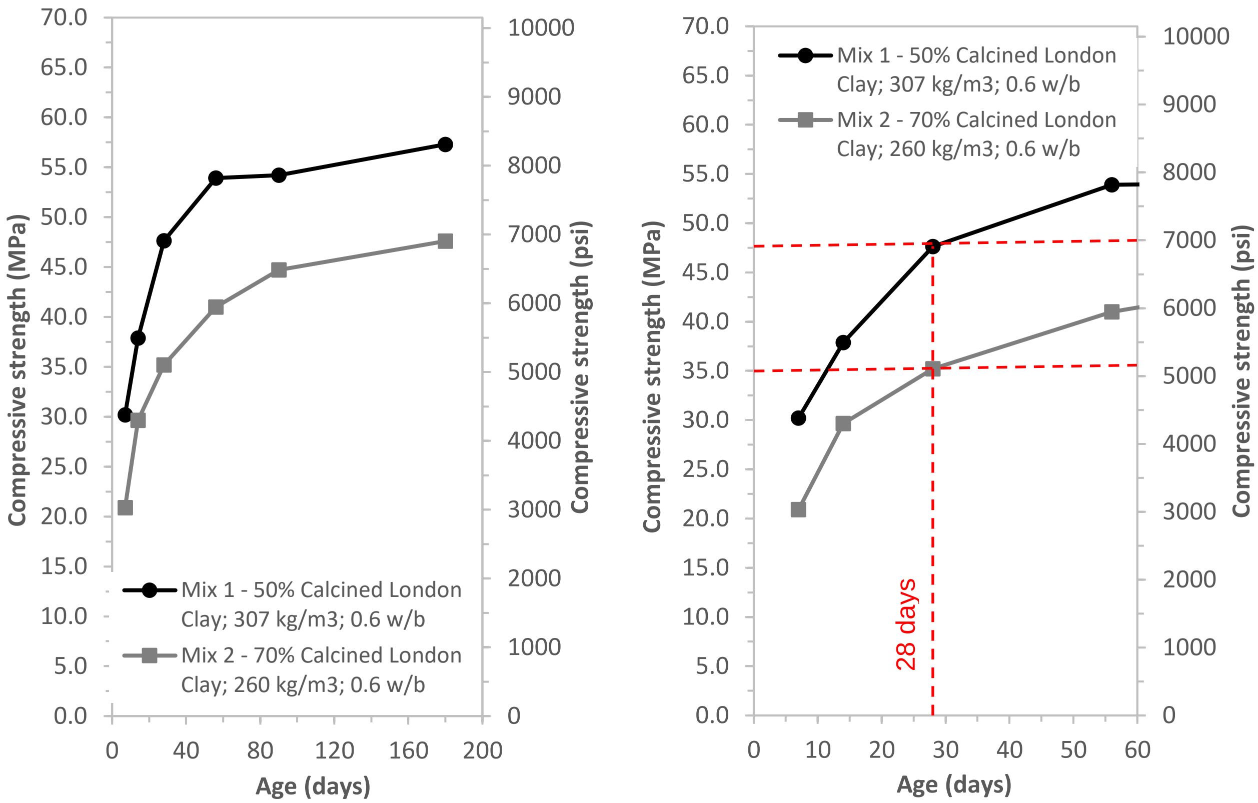

Figure 4. Strength development of concretes mixed on site with calcined London Clay; up to 180 days testing (left) and up to 56 days testing (right).

3 APPLICATION POTENTIAL IN CANADA

This innovative approach can be applied to projects within Toronto, Canada and the Americas regions. While the presented innovation has been undertaken considering London Clay, clay tunnel arisings from projects within the Americas region are derived from different geological formations. The chemical composition of the clay determines its applicability to this technology, with particular emphasis on the kaolinite content of the clay. Examining clay mineral distribution in subsoils of each physiographic region in Canada indicated varying clay mineral distributions. Figure 5 (Kodama, 1978) indicates varying frequencies of kaolinite content in clays per region. The most widespread clays of Eastern Ontario are the marine clays deposited from the Champlain Sea that occupied the lower Ottawa and St. Lawrence valleys. Champlain Sea Clay contains very small quantities of clay minerals such as kaolinite and therefore is unlikely to be suitable for use (Laventure, 1964). The Edmonton city area is underlain by proglacial lake sediments ranging in thickness. Glacial till lies below the lacustrine sediments. A summary of mineralogical compositions for Lake Edmonton Sediments (Fredlund and Dahlman, 1971) indicates varying level of Chlorite-Kaolinite percentages within samples between 10% and 30%.

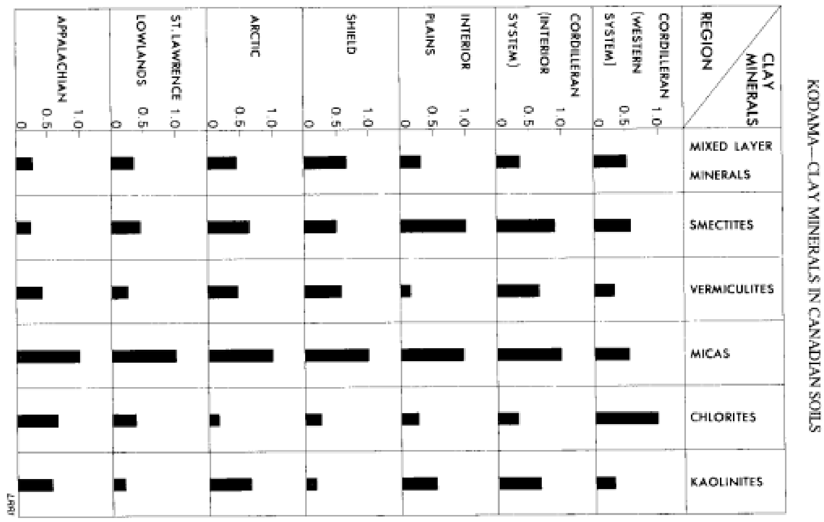

Figure 5. Occurrence frequency of clay minerals in subsoils in various physiographic regions (Kodama, 1978).

Arup are currently working on several tunneling projects with substantial quantities of excavated clay. Table 2 lists the project name and location along with the estimated quantity of clay arising from the tunneling works. It is also possible to consider this technology on projects involving large excavations. Further consideration needs to be given to the suitability of these clays for transformation into construction resources for concrete through the previously described innovative process. Alongside ongoing tunnelling projects, future candidate projects which are expected to generate substantial volumes of excavated clay are listed for consideration for further analysis.

Table 2. Current and future tunneling projects with large quantities of excavated clay in Canada.

Project	Location	Quantity (m^3) of excavated clay	Type of Clay
Eglinton Crosstown West Extension ATC1	Toronto, ON	85,000 (m^3)	Glacial Ice Deposits, Halton Formation
Scarborough Tunnel Extension	Toronto, ON	215,000	Glacial Ice Deposits, Halton Formation
Fairbank Silverthorn Trunk Storm Sewer	Toronto, ON	70,000	Glacial Ice Deposits, Halton Formation
Dickenson Road Sewer Tunnel	Hamilton, ON	6,700	Lake Warren Deposits, Glaciolacustrine silt
BART Silicon Valley CP2	San Jose, CA	37,000	Alluvium (Holocene)
Silicon Valley Clean Water Gravity Pipeline	CA	90,000	Artificial fill and Intertidal deposits (Holocene)
Ontario Line North and South	Toronto, ON	Unknown and further analysis is required to determine anticipated excavated quantities, type of clay and its suitability for transformation to calcined clay for concrete.	
Yonge North Subway Extension	Toronto, ON		
West Vaughan Sewage Servicing Project	Toronto, ON		
Stanley Park Water Tunnel	Vancouver, BC		

4 CONCLUSIONS

This paper discussed the potential for re-utilization of waste clays from excavation operations as a lower carbon supplementary cementitious material in concrete through an innovate circular approach. The work unveiled the feasibility of using lower grade, not particularly reactive, clays for use in the production of structural concrete. If the clay considered for use arises from a particular tunnelling project, then circularity can be maximised through converting the excavated clay to a supplementary cementitious material for use in concrete specific to the particular project. While this innovate approach was developed and applied as part of a major infrastructure project in London, UK, its application can be extended to other infrastructure projects. Such possibility has been briefly analysed for Canada, demonstrating potential to apply this technology in tunnelling projects in this region.

5 ACKNOWLEDGEMENTS

Regarding the “REAL” initiative, the authors would like to acknowledge the funding received by High Speed 2 Ltd. to carry out this research and the important collaboration and support of the academic partners, University of Leeds and EPFL. The REAL project is a multidisciplinary initiative co-led by ARUP (technical leadership and idea realization) and SCSJV (project and resource management, logistics and on-site tests) supported by expert industrial and academic institutions.

6 REFERENCES

Brunskill, R. W. 1997 Brick Building in Britain. Victor Gollancz in association with Peter Crawley.

Diaz, A. et al, 2022 Properties and occurrence of clay resources for use as supplementary cementitious materials. A paper of RILEM TC 282-CCL, Materials and Structures, 55:139.

Fredlund, D. G. and Dahlman, A. E., 1971. Statistical geotechnical properties of glacial Lake Edmonton sediments, Proceedings of the First International Conference on Applications of Statistics and Probability to Soil and Structural Engineering.

Guillet, G. R., 1977. Clay and Shale Deposits of Ontario.

Joseph, S. et al. 2023, Mechanical properties of concrete made with calcined clay: a review by RILEM TC-282 CCL, Materials and Structures, 56(4).

Kanavaris et al. 2022, Suitability of Excavated London Clay from Tunnelling Operations as a Supplementary Cementitious Materials and Expanded Clay Aggregate, Proceedings of the International Conference on Calcined Clays for Sustainable Concrete (CCSC 2022), Lausanne.

Kanavaris F. 2022, Circling around clay, Materials World, December/January:51-53.

Kanavaris F. and Papakosta A. 2022, Calcining excavated London Clay to produce supplementary cementitious material and lightweight aggregate, Concrete (London), July:40-42.

Kemp, S. and Wagner, D., 2006, The mineralogy, geochemistry and surface area of mudrocks from the London Clay Formation of southern England. British Geological Survey Inter-nal Report. Keyworth, Nottingham: British Geological Survey. (2006).

Kodama, H., 1979, Clay minerals in Canadian soils; their origin, distribution and alteration. Can. J. Soil Sci. 59: 37-58.

Laventure, R. S., 1964, Soluble constituents and ion exchange reaction of Champlain Sea sediments.

Papakosta, A., Kanavaris. F., Pantelidou, H. and, Burr-Hersey T., (2020) Transformation of London clay into construction resources: Supplementary cementitious material and lightweight aggregate, HS2 Learning Legacy.

Scrivener, K., Martirena, F., Bishnoi, S. and Maity, S., 2018. Calcined clay limestone cements (LC3). Cement and Concrete Research, 114, pp.49-56.

TGB, 2021.The Green Construction Board. The Routemap for Zero Avoidable Waste in Construction.