Suitability of excavated London Clay from tunnelling operations as a supplementary cementitious material and expanded clay aggregate

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Abstract. London Clay is a marine geological formation that is relatively abundant in the London Basin area in the United Kingdom. It primarily originates from reworked Jurassic shale, greensand and chalk and lateritic Eocene soils with a mineralogy consisting of kaolinite, illite, chlorite and smectites. As part of a major tunnelling project in the United Kingdom, significant volumes of London Clay will be excavated in the wider London area. While the excavated material would normally be treated as waste, sent to landfill or incorporated into landscaping, 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 in the transformation of London Clay spoil into such construction resources. It encompasses investigations on the plastic, microstructural and chemical properties of raw and calcined London Clay, 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 mixes with compressive strengths of up to 40 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.

Keywords: Calcined clay, London Clay formation, SCM, expanded clay aggregate.

1 Introduction

Population growth and rapid urbanisation in the context of climate crisis and resource depletion require the construction industry to revisit its traditional linear material sourcing and disposal practices. Alternative techniques should be adopted to respond to increasing need for built assets in an environmentally sustainable manner.

With concrete being the single most widely used building material, there is growing need for exploring new, accessible and low-carbon alternatives for its main constituents - cement and aggregates. Particularly in Europe, stock levels of the currently principal sources of Portland cement replacements, such as fly ash and ground granulated blast furnace slag (GGBS), are declining due to the gradual phase-out of the industries generating them – coal and primary steel making respectively, combined with the rising concrete demand for new developments.

Waste management and construction logistics, particularly for projects in dense, urban environments are complex to execute and challenging to budget and programme, as well as adversely impacting the environment and local surroundings. Tunnelling and deep excavations generate large volumes of spoil that need to be transported and disposed of offsite with the associated increased carbon emissions, air pollution and costs. In recent years there have been efforts to utilise such arisings in landscaping and as fill material. However, the potential to transform excavated spoil into useful construction resource like concrete has largely remained untapped so far.

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. see Fig. 1. HS2 will need to manage such large amounts of excavation arisings; particularly in the greater London area, where extensive tunnelling producing high volumes of London clay spoil, will need to be undertaken underneath central London. 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 [1].

London Clay is a geological formation abundant in the London Basin in the United Kingdom [2] which has been traditionally used brick manufacturing [3] with a mineralogy consisting mainly of chlorite, kaolinite, illite, smectite, montmorillonite. Recent developments as part of a pioneering initiative within the HS2 framework revealed that although London Clay encompasses relatively low kaolinite contents, e.g., 10-30%, it is still possible to be used as a supplementary cementitious material (SCM) in its calcined form and even be used to produce expanded clay aggregate.

Fig. 1. A High Speed 2 construction site for a concrete shaft and collected excavated London Clay.

This study provides an overview of the main objectives and results of the REAL (Re-purposed Excavated Arisings Loop) project, aiming to transform London Clay spoil to construction resources, with particular focus to the potential of using calcined London Clay as an SCM in concrete.

2 Project objectives and overview

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 useful concrete materials. Successful implementation and roll out of this circular economy approach could result in minimised waste streams to landfill avoiding the environmental impacts and costs associated with transport and disposal, improved resource efficiency, reduced need for imported materials, construction products innovation, new skills & employment and leave a legacy for the industry.

The project is focused on repurposing London Clay, which is the most frequently encountered geological formation in Greater London, including most of the tunnelling and excavation arisings in HS2 London works.

Two main outputs are targeted by processing excavated London Clay spoil:

- Calcined clay, for use as supplementary cementitious material n concrete mixes

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

The REAL project is a multidisciplinary collaborative initiative with the overarching objective to address the above challenges through examining the viability of repurposing excavation arisings to produce useful construction materials. Because of the complexity of the components of this innovation, the robustness and fitness for purpose of turning clay to resource can only be validated through discrete steps of development. Therefore, REAL is structured as a modular feasibility study with every step of the process, depending on the outcomes of the previous stages. The two key project phases are:

- Stage 1 – Proof of concept: Materials & 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 – Pilot: Site trial: On-site production of the London Clay derivatives and trial in High Speed 2 construction works

Currently, with Phase 1.a. completed; the project undergoes Phase 1.b. which focuses on the development of project specific concrete mixes. The initiative of the REAL research project aims to establish the first industrial production and application of calcined clay in continental Europe.

3 Experimental programme

A comprehensive experimental programme has been developed as part of the REAL project with focus on characterizing London Clay in its raw, but particularly in its calcined form for used as an SCM in concrete. Complementary tests are also performed to indicate suitability of excavated London Clay for the production of LWA. A description of the testing programme and properties investigated or being investigated is shown in Table 1. The tests are conducted in several specialized institutions and laboratories in Europe and the United Kingdom. It should be noted that the testing programme is progressively updated as the project evolves and once completed, further durability and material property related tests specific to HS2 needs will be conducted.

The purpose and scope of the experimental programme is to initially characterize London Clay in its raw form in terms of suitability for calcination and use mainly as a supplementary cementitious material and potentially as expanded clay aggregate. Raw London Clay has been considered and collected in several forms for the testing programme, e.g., raw as excavated, as extracted from the tunnelling boring machine with and without conditioning foams to facilitate digging, with and without moisture and chemical stabilization agents (quicklime) or wet and dry condition. Particular focus was also given to the variability of London Clay across different locations in the Greater London area as well as different depths. Further tests are conducted on calcined London Clay samples to obtain more information on calcined London Clay reactivity and suitability as SCM and expanded clay aggregates. Following the characterization tests, preliminary tests and trial mixes are carried out on pastes, mortars and concretes, to determine the effects and feasibility of calcined London Clay as SCM with reference to fresh and hardened properties, optimized calcined London Clay content and addition of limestone to potentially exploit the synergistic effects between Portland cement, calcined clay and limestone. Preliminary compressive strength tests that have been conducted and will be shown later, were based on mixes with CEM I 42.5 N, calcined London Clay and limestone in accordance with EN 206.

Table 1. Experimental programme.

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

4 Preliminary results and discussion

This section provides an overview of the main and some preliminary results on the suitability of calcined London Clay as a supplementary cementitious material and expanded clay aggregate. The section focuses on key parameters and initial findings to with regards to the investigations within the REAL project.

4.1 Suitability of calcined London Clay as an SCM – preliminary results

With regards to the suitability of clays for use in concrete in general, there are certain key parameters that are normally considered in order to indicate the reactivity of the clay in its calcined form. Perhaps the most important one, is the kaolinite content in the clay; where, low kaolinite contents indicate low reactivity and conversely, high kaolinite contents, high reactivity [4,5,6]. For this purpose, in complementarity with other relevant tests performed, TGA was conducted, and initial results are shown in Table 2. It is demonstrated that from the investigated samples, the kaolinite content of London Clay varied from 18 to 22%, classifying in it as a rather lower grade clay with respect to concrete use. However, further tests on additional samples from other locations have indicated that higher kaolinite contents may be observed in London Clay in the Greater London area.

Table 2. Information and kaolinite content in the investigated London Clay samples.

Sample No.	Location	Depth (m)	Weight loss in TGA (%)	Kaolinite content (%)
1	PVE wall - Euston area	10 – 15	2.6328	18.86
2	PVE wall - Euston area	15 – 20	2.7472	19.68
3	Euston station	18.8 – 20.3	2.6120	18.71
4	Euston station	14.5 – 16	2.8994	20.77
5	Euston station	16 – 7.5	2.0485	14.67
6	West Ruislip trial pits	2.9 – 3.2	2.4500	17.55
7	West Ruislip trial pits	2.7 – 3	1.4800	10.60
8	Thames Tideway - West	approx. 30	2.9100	20.84
9	Thames Tideway - West	approx. 30	3.0793	22.06
10	Thames Tideway - West	approx. 30	2.5134	18.00

Calcination of these initially collected London Clay samples was performed at 800 °C for one hour. Thereafter, several tests were performed on the calcined samples, including reactivity R3 test which involves isothermal calorimeter tests [7]. Results from the reactivity assessment as shown in Fig. 2. The R3 reactivity results confirmed that the reactivity of the investigated calcined London Clay samples is comparable to that of calcined clays with kaolinite contents of approximately 17-25%. Such kaolinite contents may be considered low for the production of medium strength structural concrete. It therefore had to be investigated what are the anticipated 28-day compressive strengths that could be achieved with the incorporation of calcined London Clay in concrete.

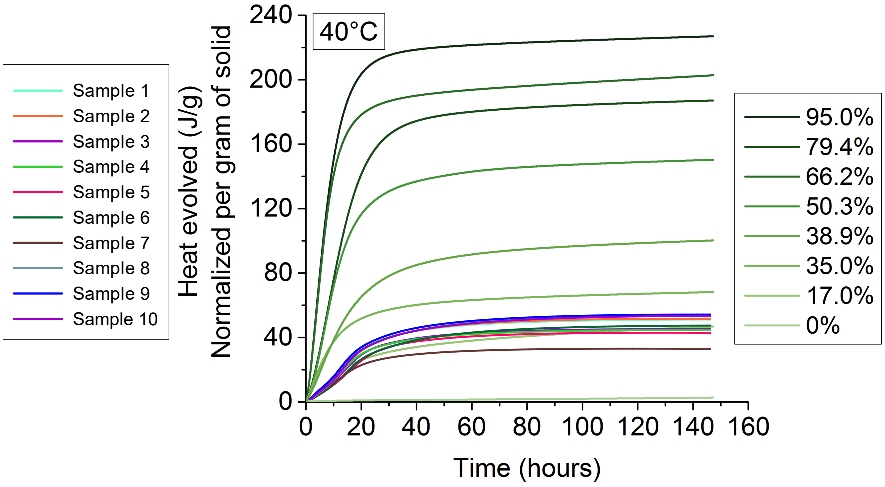

Fig. 2. Reactivity assessment of London Clay samples by R3 tests and comparison with results from other kaolinitic clays [1]. Percentages in the right-hand side legend correspond to kaolinite content.

Preliminary results on mortar mixes containing 30% calcined London Clay, 15% limestone, 5% gypsum and 50% CEM I 42.5 N are shown in Fig. 3. These are also compared to control mortar mixes with neat CEM I 42.5 N. As it can be seen, the strength development of the mortars is somewhat penalized from replacing 50% of the clinker with calcined London Clay, limestone and gypsum. However, the results also indicate that 28-day cube compressive strengths of 50 MPa can be achievable with the blends investigated and therefore, can be potentially used to produce structural concrete. With increasing the content of calcined London Clay in the mixes, it is anticipated that the 28-day strength will be further reduced and therefore, it could be suitable for lower strength applications, such as walkways and other unreinforced concrete elements with strength classes of C8/10, C12/15, C16/20 and C20/25 to EC2. Current experimental investigations are focusing on the determination of the maximum content of calcined London Clay that can be used in concrete whilst meeting the strength requirements of the aforementioned strength classes.

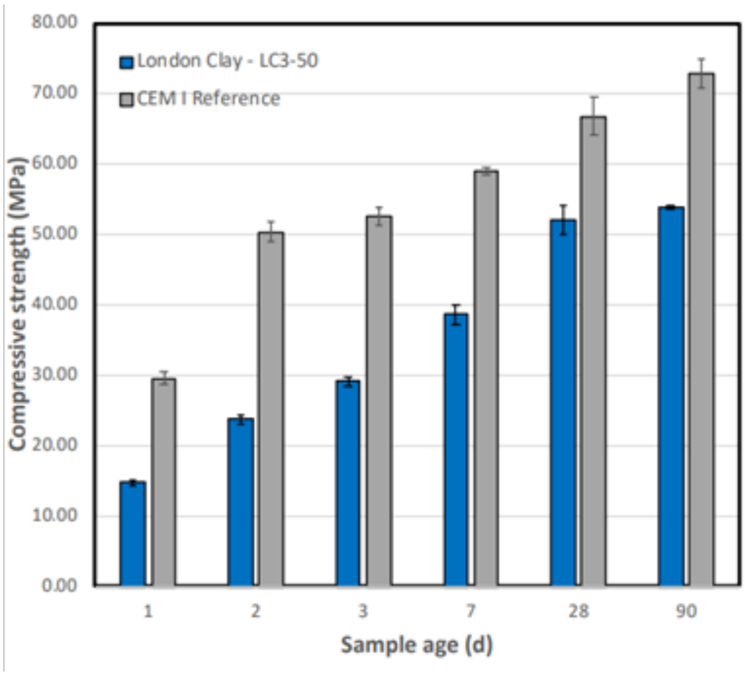

Fig. 3. Compressive strength of a mortar mix with 30% calcined London Clay (including 15% limestone and 5% gypsum) compared to a CEM I 42.5R mortar mix (right). The mixes contained 450 grams of binder per 1350 grams of sand and a w/b of 0.4.

4.2 Suitability of London Clay as expanded lightweight aggregate – preliminary results

London Clay pellets were fired in a kiln at different temperatures: 1140, 1160, 1180 and 1200 °C, for 8 minutes to produce lightweight aggregate. The variation in the firing temperature and sample location yielded different particle densities and aggregate particle sizes. Expandability results indicated that London Clay can be suitable for producing lightweight aggregates. Most of the obtained particle densities were within the desired range, i.e. varying from 250 to 450 kg/m^3. It is worth noting that, lower densities i.e. lighter aggregates were achieved in the current testing at lower temperatures, compared with the previous results from the another study [1]. This is most likely owing to the use of a small amount (0.5% by weight) of organic additive (oil) that was used in the REAL processes that aids the expandability. The additional carbon impacts from the use of the organic additive against the energy savings due to the lower heating temperatures required to achieve the London Clay LWA should be assessed in future work.

5 Summary and outlook

The REAL project attempts to establish a novel and robust approach on converting excavated London Clay from tunnelling and other excavation related works to primarily, an SCM and secondarily, expanded clay aggregate for use in concrete. Preliminary results indicate that London Clay can be used in its calcined form as a suitable SCM to produce normal strength concrete, and to also produce expanded clay lightweight aggregate. Further experiments aim to develop other concrete mixes with 28-day cube compressive strength of up to 40 MPa and Portland cement replacement levels of up to 70%. The project encompasses the potential to develop a disruptive innovative process involving operations to calcine London clay on-site directly from excavation, which is expected to significantly reduce the embodied carbon of concrete used in tunnelling operations.

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