Engineered UK clays for production of low-carbon cements

Clive Mitchell*, Tom Bide, Simon J. Kemp & Narendra Singh

British Geological Survey, Keyworth, Nottingham, UK
*Corresponding author cjmi@bgs.ac.uk

Abstract. Supplementary Cementitious Materials (SCMs) used to produce low-carbon concrete in the UK are facing increasing supply restrictions. High-kaolinite clays, used to produce calcined clay SCMs, in the UK occur in southwest England, well away from the major construction centres. The potential for low-kaolinite clays to produce SCMs is of great interest to the UK construction and minerals sectors. The research project, Engineered UK clays for production of low-carbon cements (informally known as EUREKA), aims to identify sources of low-kaolinite, clay-rich lithologies across the UK that have potential for use as SCM. Clay was identified and sampled from boreholes, brickworks, cement works, hard rock quarries, infrastructure developments, and sand and gravel pits across the UK. These included mudstones, shales, intrabasaltic palaeosols and glacial sediments. Total clay, carbonate and kaolinite contents were used to screen the clays for potential cementitious reactivity. Shortlisted clay resources will be taken forward for larger scale calcination trials and concrete testing. Preliminary results of a Life Cycle Assessment indicate that substitution of cement clinker by 30% would require around 2.8 million tonnes of clay to be extracted and calcined; increase that substitution to 50% and this increases to around 4.6 million tonnes of clay. In 2023, 3.4 million tonnes of clay were produced in the UK mainly for brick and tile production. The UK clay industry would, therefore, need to significantly increase production to meet the need to produce calcined clay for use as SCM.

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Keywords: Supplementary Cementitious Material, clay, concrete, calcination.

1 Introduction

The production of concrete is responsible for 7% of global anthropogenic CO_2 emissions, with a large proportion due to cement [1]. The climate change aspiration of UK Government is to reach Net Zero by 2050, part of which will be met via industrial decarbonisation of construction materials such as cement used in concrete.

In the UK, the carbon footprint of concrete can be reduced using Supplementary Cementitious Materials (SCMs), mainly pulverised fuel ash (PFA) and ground granulated blast furnace slag (GGBFS). However, availability of PFA and GGBFS in the UK is becoming scarcer due to the closure of coal-fired power stations and the reduction of virgin steel production. Limited availability makes other SCMs, such as pozzolana, silica fume and metakaolin, an expensive alternative. Another option to decarbonise concrete is to reduce the carbon emissions associated with cement production. These include decarbonising the electricity grid and delivery transport, use of alternative fuels such as biomass and hydrogen, and Carbon Capture, Usage and Storage (CCUS). However, to be effective these will need to be supported by Government policy and significant investment over a long period of time [2]. For example, the UK Government has recently committed £21.7 billion for CCUS over 25 years to develop the HyNet decarbonisation network and East Coast Cluster pipeline [3].

A potential source of SCMs are the large resources of natural clay (referred to as 'common clays'), with lower kaolinite contents, that occur across the UK. These represent a practical, affordable and scalable option for the decarbonisation of the cement and concrete industry. These clays would require activation to produce highly reactive cementitious materials to be used alongside Portland cement to produce concrete. Activation could take the form of calcination, alkali treatment, and/ or mechanical processing.

A field survey, carried out by the British Geological Survey (BGS), was undertaken to identify sources of 'common clay' in the UK that could be used as SCM. This was carried out as part of the research project, Engineered UK clays for production of low-carbon cements (2022-2026), informally known as EUREKA, led by Imperial College London in collaboration with the University of Leeds and the BGS [4]. In addition to the clay survey, the research aimed to develop an optimised process to convert low-purity clays into highly reactive cementitious materials, develop concretes for field applications, guide the development of cement and concretes through life cycle assessment, and disseminate the findings with industrial partners to promote uptake.

2 UK low-kaolinite clay resources for low-carbon concrete

Production of SCM by the calcination of high-kaolinite clays to produce metakaolin is well established. Research has shown that clays with moderate kaolinite (40 to 60%) and lower kaolinite (15 to 40%) can be used to produce SCM effective in producing concrete with acceptable properties [5, 6 & 7]. However, in the UK the readily available resources of kaolinite-rich clays are generally restricted to the primary and secondary kaolin deposits associated with hydrothermal alteration of feldspar minerals present in the granite intrusions of southwest England. This gives rise to the kaolin and ball clay operations of Imerys Minerals Ltd and Sibelco UK Ltd in Devon and Cornwall.

The UK is rich in 'common clay' resources with lower kaolinite contents that, if proved to be suitable for SCMs, would provide a route to the production of low-carbon concrete across the country. These clays can be obtained not just from primary mining, but also from the vast amounts present as overburden in mineral extraction sites and from ground excavation as part of infrastructure development projects where they are regarded as waste. The main challenge associated with the use of 'common clays' to produce SCMs is the lower reactivity of the mineral assemblage, which typically contains less than 30% kaolinite, various 2:1 clay minerals (e.g. smectites, illite) and impurities such as quartz and feldspar. Conventional thermal treatment to achieve reactivity is much less effective on these types of low-purity clays.

UK clay resources suitable for consideration as potential SCMs were identified by applying screening criteria: clay-rich lithology, range of clay mineral assemblages, ideally kaolinite-rich and ideally carbonate-poor. The screening was applied to the entire UK lithostratigraphic geological succession to produce a target list of geological formations and groups. These ranged from Lower Paleozoic clay units dominated by illite and chlorite, through Mesozoic clay units with varying kaolinite contents to Tertiary and Quaternary clay units where smectite joins the clay assemblage alongside illite and kaolinite. The clay units identified as potential for production of SMC were incorporated into a target map using data from the BGS Geology onshore digital geological maps of Great Britain and Northern Ireland. Sample sites were chosen by overlaying the location of mineral extraction sites from the BGS BritPits database as well as infrastructure projects such as the High Speed 2 (HS2) rail construction project.

Over a period of 2 years, 73 samples were collected from 43 sites across the UK including sites operated by Anglo American, Breedon Trading Ltd, British Gypsum (Saint Gobain), Hanson (now Heidelberg Materials UK), HS2, Marshalls Natural Stone, McQuillan Quarries, Northstone Materials, Tarmac (A CRH Company) and Wienerberger. Figure 1 shows Todhills clay quarry, operated by Wienerberger working Carboniferous Pennine Middle Coal Measures Formation mudstone for brick production, which was sampled and evaluated as part of the research. The clay units identified by the screening are listed in Table 1, this includes clay units not in the original screening list (shown in bold) that were provided by operators and were incorporated into the research.

Fig. 1. Todhills quarry, Bishop Auckland, County Durham, UK

Table 1. Potential UK clay-bearing stratigraphic units, their distribution and clay mineralogy

Time period	Stratigraphy	General clay mineralogy
Quaternary	**Alluvium***, Clay-with-flints*, Estuarine & Lake Muds, **Head brickearth*** & Glacial sediments*	Smectite, illite, kaolinite
Tertiary	**Antrim Lava Group*** & Lough Neagh Clays*	Kaolinite-dominated with vermiculite, illite
	Bovey Formation (Ball clays)	Kaolinite and illite
	Solent, Bracklesham, Thames*, Lambeth & Montrose groups.	Smectite-dominated, illite, chlorite, kaolinite
Cretaceous	Lower Greensand, Wealden* & Cromer Knoll groups.	Kaolinite and illite-dominated, berthierine/ glauconite
Jurassic	Ancholme*, Great Oolite*, Oxford Clay* & Lias* groups.	(Smectite), illite/ mica, kaolinite, (chlorite), (berthierine)
Permo-Triassic	Mercia Mudstone Group*.	Illite and chlorite dominated, occ. smectite, corrensite
Carboniferous	Tonsteins, K-bentonites, wayboards, seatearths & fireclays.	Kaolinite- or illite/smectite dominated
	Pennsylvanian: Coal Measures*, Holsworthy, Millstone Grit*, **Pennine Coal Measures*** & Warwickshire* groups.	Kaolinite-dominated, minor I/S, chlorite
	Mississippian: **Avon***, Clackmannan*, Craven*, Strathclyde, Teign Valley & Yoredale groups.	Illite-dominated, minor I/S
Devonian	Caithness Flagstone, Brecon & Ditton groups; Tamar & Meadfoot groups	Illite- and chlorite-dominated, (corrensite)
Lower Paleozoic	Moffat Shale, Hawick, Gala*, Leadhills, Tappins, Windermere, Ingleton, Skiddaw & Manx groups.	Illite- and chlorite-dominated

* The clay units sampled as part of the research are marked with an asterisk; those clay units in **bold** represent samples donated by mineral operators.

3 Clay characterisation and reactivity testing

Mineralogical characterisation of the clay samples was carried out by X-ray diffraction (XRD), Thermogravimetric/ Differential Scanning Calorimetry mass spectrometry analysis (TGA/DSC-MS) and Specific Surface Area (SSA) determination (using the 2-ethoxyethanol (ethylene glycol monoethyl ether, EGME) technique). The characterisation data will be published in full in 2026 [8] and is summarised below [9]:

- **Clay minerals**: (average) mica (26%), chlorite (3%), kaolinite (13%), smectite (3%), illite/ smectite (8%) and palygorskite (<0.1%).

- **Carbonates**: (average) e.g. calcite (5%), dolomite (4%), siderite (<1%).

- **Silicates**: (average) e.g. quartz (28%), plagioclase (3%), K-feldspar (3%), pyroxene (1%) and zeolite (<1%).

- **Others**: (average) e.g. hematite (<1%), pyrite (<1%) & gypsum (<1%).

- **SSA**: (m^2/g) ranged from 41 to 307, with an average of 131.

- **TGA/DSC-MS**: identified patterns of dehydration (50 to 300°C), dehydroxylation/ decomposition (350 to 950°C) and recrystallization (>950°C).

The clays were classified into four broad groups that were used for determination of potential as SCMs by reactivity testing as follows [9]:

Group 1: Clays containing 40% or more kaolinite. This included 8 clays with a total clay mineral content ranging from 62 to 80%. These clays exhibited the highest chemical reactivity. The best results were for clays with high-kaolinite content, low quartz content and the presence of other reactive clay minerals such as illite/ smectite.

Group 2: Clays containing 40% or more total clay mineral content but with a lower kaolinite content (15 to 39%). This included 17 clays. These clays showed a broad range of reactivities. The best results were shown by clays with low quartz contents and high total clay contents (more than 63%, with the content of kaolinite and mixed layer clays more than 45%).

Group 3: Clays containing mixed layer clays and 10% or more carbonates. This included 27 clays. These clays showed moderate reactivity which is largely attributable to the high total clay content (10-60%) and influenced by the carbonate decomposition products and secondary reactions following calcination.

Group 4: Clays containing a mixture of clay minerals, less than 15% kaolinite and a higher mica content. This included 19 clay samples. These showed the lowest reactivity. The results indicate that high mica contents (typically exceeding ~45%) are a limiting factor for chemical reactivity, even when mixed-layer clays are present.

This research indicates that low-kaolinite clays suitable for production of SCMs should contain a minimum total clay mineral content of 40%, of which mica should form less than 60% in the clay fraction. Mixed layer lays such as illite-smectite have contributed to cementitious reactivity. Higher contents of quartz, mica, smectite and carbonates tend to limit reactivity. Clays with high-carbonate content should not be discounted as some develop moderate (up to 30% carbonate) or high (up to 20% carbonate) reactivity when calcined.

Based on the samples evaluated, four geological units of those evaluated were identified as containing clays with high potential as SCMs [9] as follows with a summary of their current industrial importance to the UK and mineralogical composition:

- **Etruria Formation** (Warwickshire Group; Carboniferous). Red, purple, brown, ochreous, green, grey and commonly mottled mudstone. This is a well-known UK brick clay resource that is extracted and used in the English Midlands (Staffordshire and other parts of the West Midlands). It accounts for approximately 20% of UK brick production [10]. Mineralogical composition (based on 5 samples): Quartz 24-61%, 16-50% kaolinite, 12-31% illite/ smectite, 3-22% illite plus trace amounts of carbonate (dolomite/ calcite), feldspar, hematite, anhydrite and chlorite. Total clay mineral content, 34-73%.
- **Pennine Coal Measures Group** (Carboniferous). Interbedded mudstone, siltstone, sandstone and commonly coal seams. Upper Carboniferous mudstones are an important clay resource in the UK (mainly in the north of England), accounting for 25% of brick production [10]. Mineralogical composition (based on 13 samples): Quartz 12-47%, mica 9-58%, kaolinite 2-50%, illite/ smectite 2-21%, siderite 1-11%, K-feldspar 1-8%, plagioclase 1-10%, and chlorite 1-4%. Total clay mineral content, 43-83%.
- **Avon Group** (Carboniferous). Interbedded grey mudstones and limestones. Lower Carboniferous mudstones are an important source of raw material for cement production in the UK [11]. Mineralogical composition (based on 1 sample): Kaolinite 25%, quartz 23%, illite/ smectite 19%, mica 17%, calcite 7%, K-feldspar 2%, pyrite 2%, chlorite 2%, siderite 2%, and 1% gypsum. Total clay mineral content, 63%.
- **Glacial clays** (Quaternary). Laminated clays with variable sand contents, often related to other glacially derived sediments. Glacially derived sediments are an important source of construction sand and gravel in the UK, as well as a source of clay for brick production, used as landfill liners and flood defense material [11]. Mineralogical composition (based on 4 samples): Quartz 23-33%, mica 25-30%, calcite 1-30%, kaolinite 2-22%, illite/ smectite 3-15%, dolomite 2-6%, plagioclase 2-5%, K-feldspar 3-4%, pyrite 1% and chlorite 1%. Total clay mineral content, 31-62%.

Following the identification of low-kaolinite clays in the UK with the potential to produce SCMs, research has focused on processes for generating cementitious reactivity in the chosen clays. This has included chemical treatments (acid washes) and mechanical treatments (planetary ball milling) to increase the reactivity of the low-kaolinitic clays prior to calcination. Large pilot-scale trials have taken place using selected clays taken from quarry sites, calcined at scale and used in concrete performance testing and field trials. This research will be published towards the end of the research project (late 2026/ early 2027).

4 Life Cycle Assessment and future clay demand

A life cycle assessment (LCA) of calcined clay for use as an SCM requires evaluation of the environmental impact across all stages of its production and use. The supply chain life cycle involves the extraction, transportation, preparation and processing, calcination, grinding and distribution (Figure 2). This supply chain would typically use locally sourced raw materials and employ energy-efficient production to offer a more sustainable alternative to traditional cement components. The most carbon-intensive component of cement is the manufacturing of clinker, which requires extremely high production temperatures (about 1450° C). The production of calcined clay would require significantly lower production temperatures, typically 700-800°C [12]. Recent studies have shown that Limestone-Calcined Clay-Clinker (LC3) formulations can replace 30–60% or even more of the clinker with calcined clay + limestone [13; 14].

The Global Warming Potential (GWP) of the calcined clay production supply chain life cycle was modelled using cradle-to-gate scenarios (A1-A3; raw materials supply, transportation and manufacturing; Fig.2) following the ISO 14040 standard [15]. The LCA model for this study was built in the openLCA software provided by GreenDelta (version 2.5). The generic and background data used the life cycle inventory (LCI) from the Ecoinvent database version 3.11 Cutoff (U) [16]. The LCA results were calculated using the ReCiPe 2016 v1.03, midpoint (H) method, which translates LCI into environmental impact scores using characterisation factors at the midpoint level [17].

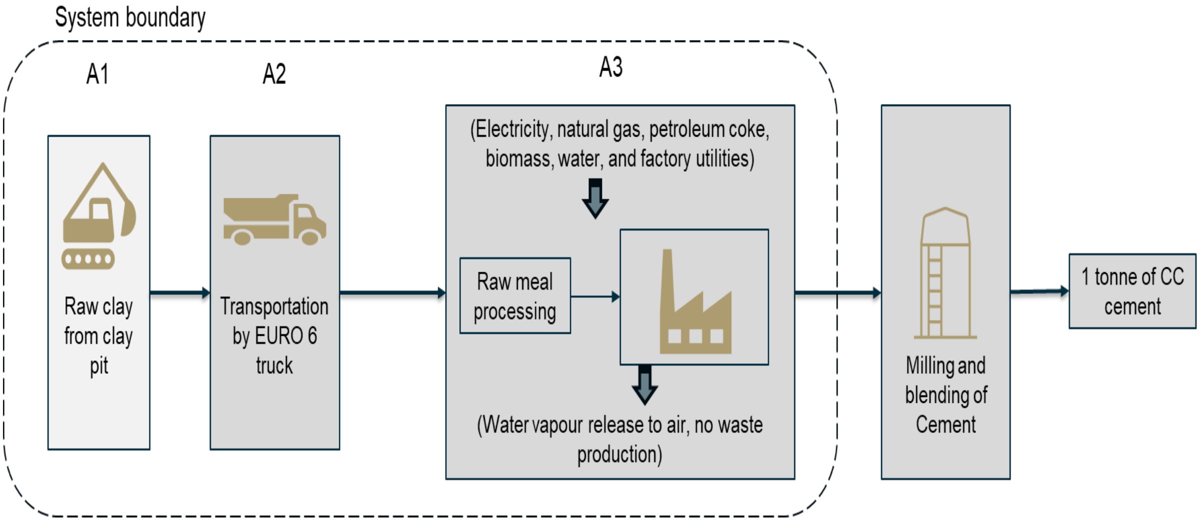

Figure 2. A system boundary figure of this study, including life cycle modules A1, A2 and A3.

The results presented in Table 2 are for production of 1 tonne of calcined clay with three scenarios using different energy sources at the manufacturing stage (A3). The results describe the carbon emissions at all stages of the supply chain. The calcination process has an impact on GWP, except for the use of renewable energy, and has also shown a variation among the thermal energy sources. The use of renewable fuel sources to produce calcined clay, 24 kg CO_2 eq. per tonne, stands out compared to fossil-based fuels, gas at 171 kg CO_2 eq. per tonne and petroleum coke at 268 kg CO_2 eq. per tonne. This compares to 812.3 kg CO_2 eq. per tonne to produce UK average Portland Cement [18].

Table 2. Global Warming Potential for production of 1 tonne of calcined clay using different sources of thermal energy.

Thermal energy	**Extraction** kg CO_2 eq.	**Transportation** kg CO_2 eq.	**Calcination** kg CO_2 eq.	**Total** kg CO_2 eq.
Petroleum coke	10.5	5.2	252.2	268
Natural gas (high pressure)	10.5	5.2	159.5	171
Renewable energy (CH)	10.5	5.2	8.2	24

CH = Switzerland.

The potential increase in the demand for clay, if large scale use of calcined clay as an SCM becomes a reality in the UK, was considered. Forecasting for the next 10 years, based on projection of UK clinker production using weighted averages of historic data [19], shows that future clinker production would be stable unless a significant change occurs in current demands of cement for the new infrastructure. Preliminary results, based on an average mass loss (moisture content and process losses) and annual clinker production, indicate that substitution of cement clinker by 30% would require around 2.8 million tonnes of clay to be extracted and calcined. A substitution of 50% would increase the demand to around 4.6 million tonnes of clay. In 2023, 3.38 million tonnes of clay were produced in the UK mainly for brick and tile production [21]. The UK clay industry would need to significantly increase production to meet the need to produce this scale of calcined clay for use as SCM. The full findings of the LCA and future clay demand projections will be published in 2026 [8].

5 Conclusions

Decarbonising the UK cement and concrete industry is important for achieving the UK Government's Net Zero target by 2050. Supplementary Cementitious Materials (SCMs) such as pulverised fuel ash and ground granulated blast furnace slag have played a key role in reducing the carbon footprint of concrete in the UK. However, their declining availability requires alternative solutions. This research demonstrates that UK common clays represent a viable, scalable resource for producing SCMs.

A systematic survey by the British Geological Survey identified numerous clay units across the UK geological succession, supported by evaluation of clay from 43 sites. Mineralogical and physical characterisation revealed significant variability in composition, with kaolinite contents ranging from 2% to 50%, alongside mica, illite/smectite, quartz, and carbonates. These variations strongly influence cementitious reactivity, which was assessed through systematic testing and classification into four groups. Clays with higher kaolinite content (>40%) and low quartz exhibited the greatest reactivity, while mica-rich clays showed reduced performance. The study establishes that a minimum total clay mineral content of 40%, combined with low quartz and mica is a key factor for achieving acceptable performance. Specific surface area further correlates with reactivity highlighting the role of particle size and morphology.

Four geological units - the Etruria Formation, Pennine Coal Measures Group, Avon Group, and Quaternary glacial sediments - emerged as promising sources of SCMs. These represent widely available resources currently exploited for brick and cement production, offering opportunities for integration into low-carbon concrete supply chains.

Preliminary findings of demand forecasting for calcined clay as an SCM indicates that large-scale implementation in the UK would require between 2.8 and 4.6 million tonnes per annum of clay over the next decade. The use of common clays as SCMs would reduce reliance on imported materials and industrial by-products, contributing to a resilient and sustainable supply chain for low-carbon construction. This aligns with broader decarbonisation strategies, including Carbon Capture, Usage and Storage (CCUS) and alternative fuels, to achieve meaningful reductions in CO_2 emissions. Ultimately, leveraging UK clay resources offers a practical, cost-effective, and nationally scalable solution to support the transition toward a low-carbon built environment.

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References

1. Global Cement and Concrete Association (GCCA). Concrete Future: Cement Industry Net Zero Progress Report 2024/25. https://gccassociation.org/wp-content/uploads/2024/11/GCCA-Cement-Industry-Progress-Report-202425.pdf, last accessed 21/11/2025. (2024).
2. Mineral Product Association (MPA). UK Concrete and Cement Industry Roadmap to Beyond Net Zero. https://thisisukconcrete.co.uk/TIC/media/root/Perspectives/MPA-UKC-Roadmap-to-Beyond-Net-Zero_October-2020.pdf, last accessed 21/11/2025. (2020).
3. Casey, D. The cement industry is proving net zero is no zero-sum game. The Manufacturer. Guest Blog. https://www.themanufacturer.com/articles/diana-casey-the-cement-industry-is-proving-net-zero-is-no-zero-sum-game/, last accessed 21/11/2025 (2025).
4. Concrete Centre. EUREKA Project. https://www.concretecentre.com/Specification/Innovative-concrete/EUREKA-Project.aspx, last accessed 21/11/2025 (2024).
5. Hanein, T, Thienel, KC, Zunino, F et al. Clay calcination technology. Mater Struct 55, 3 (2022). https://doi.org/10.1617/s11527-021-01807-6, last accessed 21/11/2025 [2022].
6. Kanavaris, F, Vieira, M, Bishnoi, S et al. Standardisation of low clinker cements containing calcined clay and limestone: a review by RILEM TC-282 CCL. Mater Struct 56, 169 (2023). https://doi.org/10.1617/s11527-023-02257-y, last accessed 21/11/2025 (2023).
7. Overmann, S, Vollpracht, A & Matschei, T. Reactivity of Calcined Clays as SCM – Review. Materials, 17, 312. https://doi.org/10.3390/ma17020312, last accessed 21/11/2025 (2024).
8. Kemp, SJ, Bide, T, Mitchell, CJ, Pearson, M, Singh, N, Dhandapani, Y, & Wong, H. Identifying UK mudrocks for low-carbon cement production. In Press. (2026).
9. Tole, I, Dhandapani, Y, Kemp, SJ, Marsh, ATM, Mitchell, CJ, Black, L, Wong, H & Bernal, SA. Impact of the Mineralogy of Low-Purity Clays on their Suitability as Supplementary Cementitious Materials. Cement & Concrete Research, 204,108211. https://doi.org/10.1016/j.cemconres.2026.108211 (2025).

10. Mitchell, CJ & Wrighton, C. Mineral planning factsheet: Brick clay. British Geological Survey, 17pp. https://nora.nerc.ac.uk/id/eprint/532490/, last accessed 21/11/2025 (2022).
11. Cameron, DG, Evans, EJ, Idoine, N, Mankelow, J, Parry, SF, Paon, MAG & Hill, A. Directory of Mines and Quarries 2020: British Geological Survey. https://www.bgs.ac.uk/mineralsuk/download/directory-of-mines-and-quarries-2020/, last accessed 21/11/2025. (2020).
12. Papakosta, A, Fragkoulis, K, Pantelidou, H, & Burr-Hersey, T. Transformation of london clay into construction resources: Supplementary cementitious material and lightweight aggregate. *HS2 Learning Legacy*. https://learninglegacy.hs2.org.uk/document/transformation-of-london-clay-into-construction-resources-supplementary-cementitious-material-and-lightweight-aggregate/; last accessed 26/11/2025 (2020).
13. Junior, E, De Sales Braga, N, & Barata, M. Life cycle assessment to produce LC³ cements with kaolinitic waste from the Amazon region, Brazil. Case Studies in Construction Materials 18 e01729 https://doi.org/10.1016/j.cscm.2022.e01729; last accessed 26/11/2025. (2023).
14. Shah, I H, Miller, S A, Jiang, D, and Myers, R J. 2022. Cement substitution with secondary materials can reduce annual global co2 emissions by up to 1.3 gigatons. *Nature Communications*, Vol. 13(1), 5758. DOI
15. Finkbeiner, M, Inaba, A, Tan, R, Christiansen, K, & Klüppel, H-J. The new international standards for life cycle assessment. The International Journal of Life Cycle Assessment, Vol. 11(2), 80–85. https://doi.org/10.1065/lca2006.02.002; accessed 26/11/2025. (2006).
16. Evoinvent. 2025. Ecoinvent v3.11. Evoinvent, Vol. https://ecoinvent.org/ecoinvent-v3-11/.
17. Huijbregts, M A, Steinmann, Z J, Elshout, P M, Stam, G, Verones, F, Vieira, M, Zijp, M, Hollander, A, and Van Zelm, R. 2017. Recipe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment*, Vol. 22(2), 138–147. https://link.springer.com/article/10.1007/s11367-016-1246-y ,
18. MPA Cement. Annual cementitious. Data sheet. Mineral products association. https://cement.mineralproducts.org/MPACement/media/Cement/Industry-Statistics/2024/2024-10-08_Annual_cementitious.pdf; last accessed 26/11/2025. (2024).
19. Billah, B, King, M L, Snyder, R D, and Koehler, A B. 2006. Exponential smoothing model selection for forecasting. *International journal of forecasting*, Vol. 22(2), 239–247. DOI,
20. Internation EPD System. UK Average Portland Cement Sector EPD. https://www.environdec.com/library/epd5825, last accessed 26/11/2025. (2022).
21. Bide, T, Idoine,TN, Evans, E, Raycraft, ER & Mankelow, J. UK Minerals Yearbook 2024. British Geological Survey. https://www.bgs.ac.uk/mineralsuk/statistics/uk/;last accessed 26/11/2025 (2025).