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Energy consumption in the production of calcined kaolinitic clays for use as supplementary cementitious materials

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Calculation of energy consumption is crucial for the evaluation of the economic viability and environmental impact of thermal processes involved in cement production. As calcined clays become more widely accepted as supplementary cementitious material (SCM) around the world, it becomes very important to reliably predict the energy requirements for the industrial calcination of clays. In this study, a simple mathematical model is developed to estimate the calcination energy required for the conversion of kaolinite into metakaolin considering the drying and dehydroxylation process. The model was developed using seven natural clays with varying chemical compositions and a wide range of kaolinite contents (73–25%). The two key input parameters, namely, moisture content and kaolinite content, were found to be sufficient for obtaining a reasonable prediction of the energy demand ($R^2 = 0.97$). In addition, the study found that the associated minerals also have a slight influence on the calcination energy, with iron-rich clays exhibiting relatively lower energy demand compared to quartz-rich clays. The model was validated with 22 other clay samples and the results indicate that good estimates of energy requirements for the calcination process can be made and that the model can be used satisfactorily for the design of clay calcination processes.

Keywords: calcination energy/calcined clay/cementitious materials/modelling/sustainability/thermal analysis

Notation

C_c	specific heat capacity
C_w	specific heat of water
E_c	calcination energy
E_t	total energy
H_x	cumulative energy consumed at 300°C
H_y	cumulative energy consumed at 150°C
H_2	cumulative energy corresponding to the onset of dehydroxylation (T_2)
H_3	cumulative energy corresponding to the completion of dehydroxylation (T_3)
K	kaolinite content (%)
L_w	latent heat of vaporization of water
M_0	mass of sample at 30°C
M_1 or M_{T_1}	mass of the sample at 200°C
M_{T_2}	mass of the sample at onset of dehydroxylation (T_2)
M_{T_3}	mass of the sample at completion of dehydroxylation (T_3)
m	moisture content (%)
T_0	initial solid temperature (30°C)
T_2	onset temperature of dehydroxylation
T_3	completion temperature of dehydroxylation
T_f	final solid temperature (100°C)
T_x	upper temperature limit (300°C)
T_y	lower temperature limit (150°C)

Introduction

Portland cement is globally the most widely used construction material because of the widespread availability of the raw materials at relatively low cost. However, the production of Portland cement is energy-intensive and releases significant amounts of carbon dioxide, which poses a significant environmental challenge (Gartner, 2004). To mitigate these issues, a portion of the Portland cement clinker is commonly replaced with supplementary cementitious materials (SCMs) in mortars and concrete. This approach not only reduces the environmental footprint of cement and allows an increase in its production, but also enhances the workability, strength and durability performance of concrete. Although many SCMs such as fly ash, slag and silica fume are currently being used, calcined clay stands out as the most viable option for the future due to its relatively easy availability and the possibility to replace more than 50% of clinker in limestone calcined clay cement (LC³) blends (Alujas Diaz *et al.*, 2022; Kaminskas *et al.*, 2020; Sabir *et al.*, 2001; Shah *et al.*, 2020; Yoon *et al.*, 2022).

Clay is a naturally occurring material primarily composed of fine-grained minerals, with particles typically less than 2 μm in size, exhibits plasticity when mixed with water and hardens upon drying. Clay consists of tetrahedral silicate and octahedral aluminate sheets, and forms a structure that can be categorised as a 1:1 clay

mineral like kaolinite and halloysite; or 2:1 clay minerals such as smectite and illite (Bergaya and Lagaly, 2013; Huggett, 2020; Kumari and Mohan, 2021; Srodon, 2006). In the natural state, clays have a well-ordered lattice structure, and are highly stable and unreactive. Consequently, activation processes, such as thermal, mechanical and chemical treatments, are required to alter the crystalline structure and to improve the pozzolanic reactivity to allow their use as SCMs (Amin *et al.*, 2012; Avet *et al.*, 2018; Fernandez *et al.*, 2011; Fitos *et al.*, 2015; Mitrovic and Zdujic, 2014). Thermal activation is the most commonly used activation process, wherein the hydroxyl groups of clay minerals are removed by dihydroxylation, producing disorder in the structure that enhances the dissolution kinetics of Si and Al elements. The clay particles undergo a series of conversions during the heating process. Between 50 and 200°C, free water present on the surface or between the interlayer of clay minerals is removed. With the increase in calcination temperature, dehydroxylation occurs, which is characterised by the removal of structural hydroxyl groups attached to the octahedral layer (Bich *et al.*, 2009; Dhar and Bishnoi, 2024a, 2024b; Garg and Skibsted, 2019; Hanein *et al.*, 2022). The dehydroxylation temperature range for a particular clay depends on the degree of crystallinity and type of clay minerals. In general, 1:1 clays dehydroxylate around 750–800°C, and 2:1 clays require higher temperatures, often approaching 900°C (Dhar and Bishnoi, 2025b; Hollanders *et al.*, 2016). This phase transformation is an endothermic process and is represented in Equation 1. The calcination temperature is carefully chosen, as heating beyond optimal range results in over-calcination and this significantly reduces the pozzolanic reactivity of the clay (Dhar and Bishnoi, 2025a, 2025b). There are two primary methods for calcination: static and flash calcination. Static calcination uses a slower heating rate and longer residence times, ranging from minutes to hours, for the transformation of kaolinite into metakaolin. In flash calcination, however, clays are exposed to high temperature only for few seconds.

Mechanical activation involves the grinding of materials using milling devices, such as rolling mills, mixer mills and planetary mills to induce physical and chemical transformations in clay minerals. The process is controlled by the rate of stress and energy transfer efficiency, which are influenced by parameters such as ball-to-powder mass ratio and the rotation speed. This treatment decreases the crystallinity and enhances the amorphisation of clay minerals; it also significantly modifies the surface area and morphology (Amin *et al.*, 2012; Fitos *et al.*, 2015). While in chemical activation, phosphoric acids or alkaline media are used to increase the reactivity of clays by dissolving the crystal structure and creating an SCM (Asuha *et al.*, 2020; Baki *et al.*, 2022; Khalifa *et al.*, 2019, 2020; Komadel and Madejova, 2013; Palkova *et al.*, 2021). Among the various activation methods studied at the laboratory level, thermal treatment has been successfully scaled up to industrial production. Several pilot plant studies have been done to demonstrate the viability and robustness of the technology (Almenares *et al.*, 2017; Bishnoi, 2020; Emmanuel *et al.*, 2016;

Vizcaino-Andres *et al.*, 2015) and the pozzolanic reactivity of calcined kaolinite clays was found to be similar or in some cases higher than the laboratory results.

The economic feasibility of using clays as a raw material is influenced by several factors, including the location of the clay deposit, the mineralogical composition of the clay, the moisture content of the raw material and the processing technology employed (Joseph *et al.*, 2016; Sanchez Berriel *et al.*, 2016). While extensive studies have explored the chemical and mineralogical criteria necessary for selecting suitable raw clays (Chomyen *et al.*, 2019; Danner *et al.*, 2018; Hemalatha and Santhanam, 2018; Lorentz *et al.*, 2018; Maier *et al.*, 2021), there is limited literature about the energy demand for the conversion process of kaolinite into metakaolin. Schieltz and Soliman (1964) calculated the theoretical heat requirement of the dehydroxylation process based on enthalpic data at constant pressure and temperature. Similarly, Hanein *et al.* (2022) reported a minimum energy requirement of 1513 kJ/kg for metakaolin production, but both the calculations excluded the energy required to remove free water and were based on pure clays.

In practical applications, energy demand is significantly influenced by the purity of the clay and the pre-processing, that is the drying of kaolinite clays. A simple model to estimate the energy demand of natural clays based on specific input parameters is lacking in the literature. Furthermore, while some studies have examined the effect of impurities on phase transformation, their impact on energy consumption has not been investigated. This paper focuses on quantifying the calcination energy of kaolinitic clays and correlating it with their chemical composition. A mathematical model has been developed using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) techniques to predict calcination energy. It is expected that a better understanding of the energy consumption of clays will provide valuable insights into the economics of the calcination process and serve as a tool for optimising calcination energy design.

Experimental study

In this study, naturally available clays were obtained from cement companies operating in various continents. The samples were selected to ensure a wide range of kaolinite contents and mineralogical compositions relevant to the cement industry. The clay samples were characterised with X-ray fluorescence (XRF), TGA and X-ray diffraction (XRD) techniques. The chemical content was determined from XRF using a Bruker S2 Puma series instrument. The pressed pellet method was adopted, in which boric acid was used as a binder. The results of oxide composition were complemented with the loss on ignition (LOI) values calculated from 100 to 1000°C. XRD was used to identify the crystalline phases of powder clay samples. In this study, a Bruker D8 Advance Eco diffractometer was used with a diffraction pattern recorded between 2-theta values from 5° to 65°. The peaks were identified in TOPAS software by matching the peaks of the mineral phases

from the Inorganic Crystal Structure Database (ICSD) and the Crystallography Open Database (COD). Both TGA and DSC experiments were run simultaneously in a Setaram Labsys instrument. About 45 mg of the sample was taken and heated at 20°C/min in a nitrogen atmosphere. The TGA was done to quantify the kaolinite content by determination of weight loss due to the dehydroxylation process. The first derivative of the TGA curve was used for the identification of the exact temperature range of decomposition (Snellings *et al.*, 2022).

Table 1 lists the oxide composition and LOI values of clay samples used in this study. The chemical requirements mentioned in ASTM (2022) for natural or calcined pozzolan are (silicon dioxide (SiO₂) + aluminium oxide (Al₂O₃) + iron (III) oxide (Fe₂O₃)) > 70% and sulfur trioxide (SO₃) < 4%. The comparison of the experimental results with the standard specifications shows that all the clay samples fulfil the criteria and qualify for the Class N group of pozzolan. Moreover, chemical criteria that are often adopted for the selection of clays as SCM include silicon dioxide < 60%, aluminium oxide > 18%, LOI > 7% and Al₂O₃/SiO₂ ≥ 0.3% (Alujas Diaz *et al.*, 2022; Bishnoi, 2020). B1, B2, C1, C2, C3 and C4 clays satisfy all the criteria and consist of kaolinite clay minerals, whereas the D1 clay has lower LOI values, which indicates that the kaolinite content is less than 40%.

The XRD analysis was performed to determine the mineralogy of the clay samples. The Rietveld refinement included various clay mineral phases, such as kaolinite, nacrite, dickite, chlorite, muscovite and illite, as well as non-clay minerals, like iron hydroxides, carbonates and quartz. The results indicate that kaolinite is the predominant clay mineral in all samples (see the Appendix, Figure 7). B1 contains quartz as the main impurity, while B2 and C1 are characterised by the presence of iron hydroxides. C2 and C3 samples contain quartz and iron hydroxides as minor phases, whereas C4 clay exhibits illite and quartz as the primary impurities. D1 shows a high quartz content with minor illite impurities. More details about the mineralogy of samples can be found elsewhere (Dhar *et al.*, 2025).

Figure 1 represents TGA curves of different clays as a function of calcination temperature. The temperature range for calculating mass loss was selected based on the DTG curve, as it is more

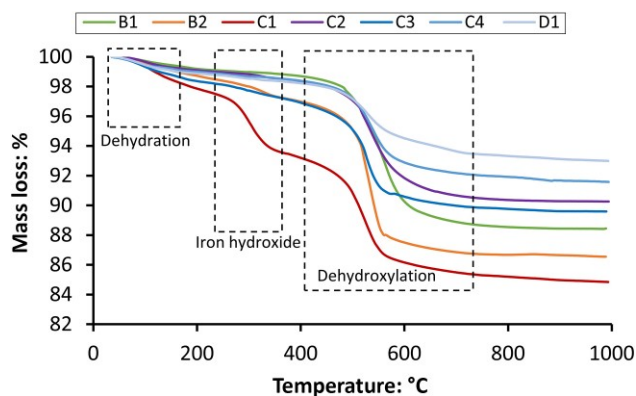


Figure 1. Thermogravimetric analysis (TGA) curves of raw clays

sensitive to small mass changes. The results show interesting features, as iron-rich clays dehydroxylate at slightly lower temperatures compared to the other clays. The order of kaolinite content in the clays is B1 ≈ B2 (73%) > C1 ≈ C2 (54% and 53%) > C3 (50%) > C4 (43%) > D1 (24%).

Modelling approach

The calcination energy is primarily influenced by the moisture content of the raw material and the kaolinite content of the clay, making these critical input parameters for the model (Hanein *et al.*, 2022). Specific heat capacity, which affects the energy needed to raise the temperature of the clay, was also considered in the model. The model was developed based on the following assumptions: (a) a partial recovery of heat is carried out until practically feasible; (b) the specific heat capacity remains constant throughout the calcination process; (c) energy is recovered from the clay particles during the cooling stage; and (d) the thermal process is assumed to be 100% energy efficient. These key parameters and assumptions were essential in establishing a simple and reliable mathematical model. The influence of these individual parameters can be easily added to the model presented to obtain calcination energy values in practical scenarios. These parameters will depend on the design of the calcination and associated equipment.

Table 1. Chemical composition of raw clays

Clay	SiO ₂	Al ₂ O ₃	TiO ₂	MnO ₂	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	SO ₃	P ₂ O ₅	LOI
B1	45.38	33.37	1.6	0.01	1.16	1.23	0.33	1.28	0.24	0.16	0.58	13.85
B2	33.95	30.84	2.06	0.06	16	0.32	1.04	0	0.73	0.01	0.1	14.69
C1	25.13	27.69	2.66	0.14	25.12	0.27	1.13	0	0.66	0.02	0.09	16.72
C2	47.90	25.47	1.12	0.04	8.44	0.59	1.82	1.1	0.77	1	0	10.18
C3	48.08	31.32	0.54	0.04	5.79	0.20	1.44	1.35	0.83	0.08	0.04	10.02
C4	54.79	28.4	1.75	0	2.31	0.25	1.34	1.3	0.88	0.12	0	8.5
D1	63.78	21.12	1.15	0.03	3.79	0.50	1.47	1.08	0	0.06	0	6.83

Note: SiO₂, silicon dioxide; Al₂O₃, aluminium oxide; TiO₂, titanium dioxide; MnO₂, manganese dioxide; Fe₂O₃, iron (III) oxide; CaO, calcium oxide; MgO, magnesium oxide; K₂O, potassium oxide; Na₂O, sodium oxide; SO₃, sulfur trioxide; P₂O₅, phosphorus pentoxide; LOI, loss on ignition

Drying of the clay is an endothermic process that requires energy to remove free or surface-adsorbed water from the clay particles before calcination. The significance of drying energy becomes particularly evident in clays with high moisture content. For example, Hanein *et al.* (2022) reported that for clays with moisture content of 40%, the energy required for drying exceed the energy needed for the dehydroxylation process. This underscores the importance of accounting for drying energy in the overall energy balance, especially since many clays tend to have significant moisture content. The magnitude of this moisture content is influenced by factors such as the type of clay mineral and the humidity of the surrounding environment. The expression used to determine the moisture content is provided in Equation 1:

$$1. \quad \text{Moisture content (m)} = \frac{M_0 - M_1}{M_1} \times 100$$

where M_0 is the mass of the sample at ambient temperature, and M_1 is the mass of the sample at 200°C (at which drying can be assumed to have been completed).

The calcination energy can be calculated by determining the kaolinite content in the clay samples. TGA is a common method used to estimate kaolinite content by measuring the mass loss associated with the dehydroxylation process. In TGA, the onset and offset temperatures for dehydroxylation are selected based on the inflection points, and Equation 3 was used to quantify the kaolinite content. However, TGA involves the use of an expensive instrument, so may not be readily available in all laboratories. In such cases, kaolinite content can be estimated using a more accessible furnace and balance method, where the onset temperature is assumed to be 350°C and the offset temperature 700°C. In addition, the mass at 200°C is measured to represent the dry mass of the sample. In the present study, kaolinite content was determined using both the oven and TGA methods to evaluate the influence of the test method. A comparison of the results in Figure 2 revealed a high correlation factor of 0.98, indicating that the oven method can be a reliable alternative to TGA.

$$2. \quad \text{Kaolinite}(K) = \frac{M_{T_2} - M_{T_3}}{M_{T_1}} \times \frac{100}{14}$$

where M_{T_1} , M_{T_2} and M_{T_3} denote the dry mass of the sample (200°C), the mass at the lower dihydroxylation temperature range and the mass at the upper dehydroxylation temperature range (i.e. $T_2 = 350^\circ\text{C}$ and $T_3 = 700^\circ\text{C}$), respectively, and 14% is considered as the mass loss due to the conversion of pure kaolinite to metakaolin.

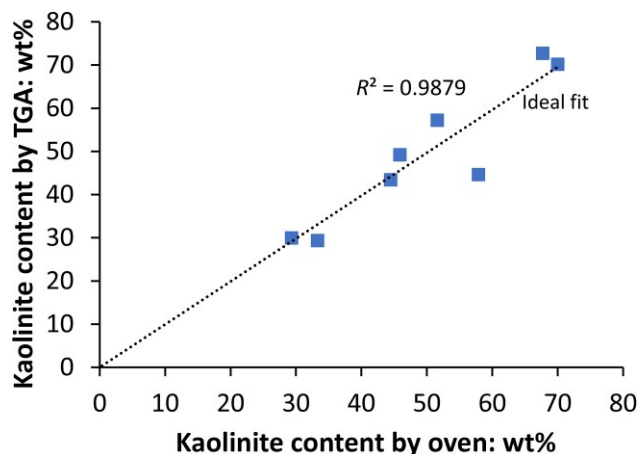


Figure 2. Correlation between oven and TGA method for kaolinite quantification

The DSC technique was used to measure the specific heat capacity of clays. The slope of the cumulative DSC curve in the temperature range of 150–300°C was taken as it appears to be constant (see the Appendix, Figure 8). The specific heat capacity was calculated from Equation 3:

$$3. \quad \text{Specific heat capacity}(C_c) = \frac{H_x - H_y}{T_x - T_y}$$

H_x and H_y represent the cumulative energy consumed at 300°C (T_x) and 150°C (T_y), respectively.

The energy absorbed by the clay sample in the dehydroxylation temperature range serves as an indicator of the calcination energy. The DSC curve was utilised to estimate the total absorbed energy during the dehydroxylation range, from T_2 to T_3 . To calculate the calcination energy, the energy absorbed due to specific heat capacity in the same temperature range was subtracted, as described in Equation 4.

$$4. \quad \text{Calcination energy}(E_c) = \frac{(H_3 - H_2) - C_c \times (T_3 - T_2)}{K}$$

where H_2 and H_3 are the cumulative energies consumed at the beginning and end of calcination (i.e. T_2 and T_3). The total energy requirement for the calcination process is then determined by accounting for both the calcination energy and drying energy. This includes the energy consumed during the release of free water and the latent heat of vaporisation. The developed model calculates the net heat supplied, taking into consideration the effect of heat recovery during the cooling stage. The computation of the total energy is summarised in Equation 5.

$$\text{Total energy}(E_t) = ((T_f - T_0) \times C_w + L_w) \left(\frac{m}{100} \right) + (E_C \times k + C_c(T_f - T_0)) \frac{(100 - m)}{100}$$

where T_f is the final solid temperature; T_0 is the initial solid temperature; C_w is the specific heat of water ($4.2 \text{ (J/g)}^\circ\text{C}$); and L_w is the latent heat of water (2240 J/g).

Calculation for energy demand of kaolinite clays

The input parameters, such as moisture, kaolinite content and specific heat capacity, of selected clays were determined, and are given in Table 2. The moisture content was found to vary from 0.5 to 1.6%. There was a wide range of kaolinite content ranging from 29% in D1 clay to 73% in B2 clay. Specific heat capacity was calculated for each clay using Equation 4 and the average value was found to be $2.15 \text{ (J/g)}^\circ\text{C}$ with a coefficient of variation of 0.16. Likewise, the calcination energy per kaolinite content seems to be somewhat scattered. The average calcination energy was calculated as 1489 kJ/kg , with a coefficient of variation of 0.16. Samples with similar values of kaolinite content showed some differences, which may be attributable to the effect of associated minerals present in the kaolinite clays.

The total energy required for the calcination process was first calculated by the energy consumed during both the drying and dehydroxylation stages. However, since the clay samples in the present study had a low free moisture content at the time of testing, the contribution of drying to the total energy was negligible.

Figure 3 presents the calculated energy requirements for the calcination of the various clays studied. The results indicate that B1 clay exhibited the highest energy consumption, whereas D1 clay required the least. The broad range of kaolinite content among the selected samples resulted in significant variations in energy demands. High-grade kaolin clays, such as B1 and B2, required more energy for conversion to metakaolin compared to medium-grade kaolin clays.

In practical calcination units, energy supplied for the process is partially recovered during the cooling stage. Heat recovery systems are designed to capture and reuse the thermal energy from

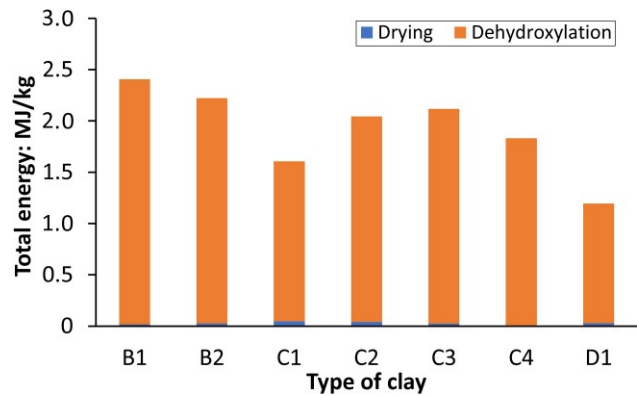


Figure 3. Total energy required for production of calcined clays

the clays as their temperature decreases, typically until the solid temperature drops to $100\text{--}200^\circ\text{C}$. This approach was incorporated into the energy model, allowing for the calculation of net energy requirements after accounting for heat recovery. Figure 4 breaks down the total energy consumption into net energy demand and the energy recovered through heat exchange. It was observed that approximately 53% of the total energy was recovered, significantly reducing the net energy required for calcination. For instance, the energy required to produce metakaolin from B1 clay was calculated to be 1119 kJ/kg , closely aligning with the

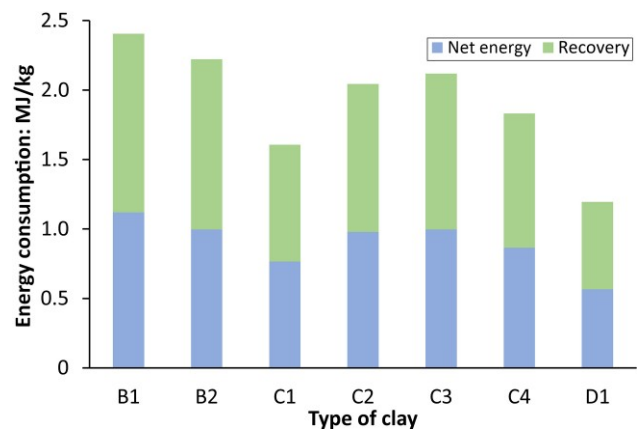


Figure 4. Net energy demand of calcined clays used in the present study

Table 2. Values for input parameters of clay samples

Clay sample	Moisture content, m : %	Kaolinite content, k : %	Specific heat capacity, C_c : $(\text{J/g})^\circ\text{C}$	Calcination energy: kJ/kg
B1	0.60	70.19	2.54	1329
B2	0.89	72.71	2.74	1088
C1	1.55	55.37	1.98	1090
C2	1.38	57.22	1.89	1440
C3	0.78	49.24	2.30	1671
C4	0.56	43.43	1.87	1669
D1	0.68	29.34	1.72	1471

theoretical value of 1145 kJ/kg reported for kaolinite clays in the literature (Hanein *et al.*, 2022).

Interestingly, the relationship between kaolinite content and net energy demand was found to be only moderately linear, with a correlation coefficient of 0.66. This suggests that other factors, such as the chemical and mineralogical composition of the clays, also significantly influence the energy requirements. Notably, clays with high iron content demonstrated lower energy demands for the same kaolinite content compared to silica-rich clays. For example, B2 clay, which contains 16% iron content, required 11% less energy than B1 clay. In addition, C1 clay, with 24% iron content, exhibited approximately 25% lower energy demand compared to C2 clay. This indicates that the presence of iron reduces the energy required for the calcination of clays. Iron impurities lower the energy demand of clays and the reduction was found to depend on the amount of iron content. A possible explanation for this observation is that quartz mineral itself undergoes an endothermic α -to- β quartz phase transition around 573°C (Speil *et al.*, 1945), which can marginally contribute to the overall energy consumption. In addition, iron-rich clays may facilitate better heat transfer due to the higher thermal conductivity of iron-bearing phases, potentially leading to more efficient dehydroxylation and lower measured energy demand.

Performance evaluation of the developed model

The validation of the proposed mathematical model was conducted using a diverse set of 22 different clay samples (Table 3). For each of these samples, all input parameters – namely, moisture content, kaolinite content, specific heat capacity and calcination energy – were initially calculated based on the equations specified

Table 3. Characteristics of clays used for validation of model

Clay ID	Moisture: %	Kaolinite content: %
L1	0.4	32.9
L2	11.9	35.1
L3	0.9	40.0
M1	7.5	55.7
M2	1.5	59.4
M3	2.4	61.5
M4	0.8	62.9
M5	1.3	64.1
M6	0.7	64.7
M7	0.4	66.2
M8	1.5	68.7
M9	1.6	70.3
M10	0.7	70.6
M11	1.5	71.7
M12	1.1	75.9
H1	1.3	81.0
H2	0.8	81.1
H3	3.4	82.9
H4	5.1	84.4
H5	0.3	84.9
H6	2.9	85.3
H7	3.5	92.6

in the previous sections. Then, the actual energy consumption for each clay sample was determined. The results indicated that the linear correlation between kaolinite content and energy consumption was moderate, with a correlation coefficient of 0.61 (Figure 5). This suggests that, while kaolinite content is a significant factor, other associated minerals may also have an influence on the energy demand during calcination.

The performance of the model was evaluated by comparing the actual energy demand with the predicted results by reducing the number of input parameters needed for accurate energy estimation. The average specific heat capacity and calcination energy, derived from the initial calculations, were used to predict energy consumption by using only moisture content and kaolinite content as input parameters. This aim of this approach was to streamline the model, as fewer input parameters would facilitate easier and more efficient calculations. The comparison between actual and model-predicted energy demand (Figure 6) showed

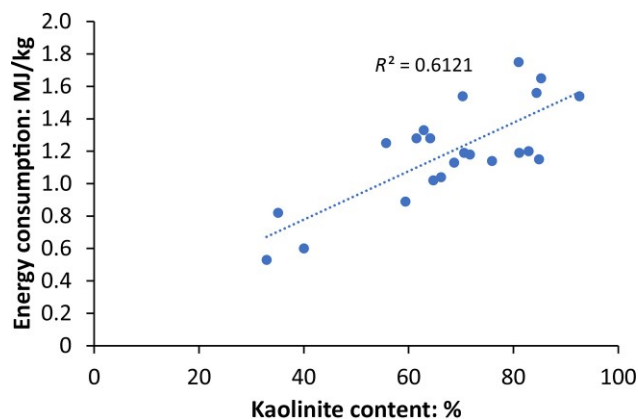


Figure 5. Correlation between kaolinite content and energy consumption for metakaolin formation

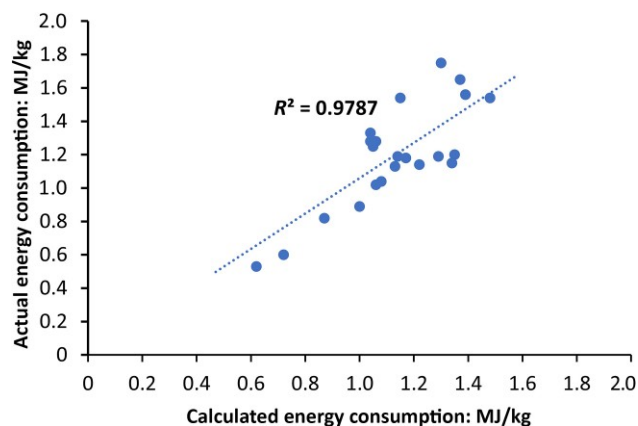


Figure 6. Comparison of actual energy consumption with calculated model predictions

that, out of the 22 samples, 19 samples exhibited an error margin of less than 20%. This demonstrates that a reasonable estimation of energy requirements for producing calcined clays can be achieved using just two key parameters: moisture content and kaolinite content.

It is important to note that some discrepancies between predicted and actual values are expected when using average specific heat capacity and calcination energy, as these properties can vary among different clay samples. However, the average values obtained from the diverse range of clays used in this study appear to provide a satisfactory approximation. Given the broad spectrum of clays examined, the average values for specific heat capacity and calcination energy are deemed adequate for practical applications.

Thus, the findings of this study suggest that a quick and effective economic analysis of the energy demand for converting kaolinite into metakaolin can be conducted with minimal input parameters. Moisture content and kaolinite content, both of which can be easily determined, offer a practical and simplified approach to energy estimation. This underscores the robustness and utility of the model, particularly in scenarios where rapid decision making and efficiency are paramount.

Conclusions

In this study, a simple mathematical model was developed to estimate the energy required for converting kaolinitic clay into metakaolin using a thermal activation process, considering both the dehydration and dehydroxylation processes. For accurate estimation, the model requires four input parameters: moisture content, kaolinite content, calcination energy and specific heat capacity. However, the authors' findings demonstrate that, even with just two primary parameters (namely, moisture content and kaolinite content), a reliable estimate of energy consumption can be achieved, which would help in the prediction of economic performance for calcined clay production. The results also highlight that the mineralogical composition of the clay influences the total energy demand, as only a moderate correlation between energy consumption and kaolinite content was observed. This indicates that other associated minerals, such as iron and quartz, also have an impact on energy requirements, with iron-rich clays generally requiring slightly less energy than quartz-rich clays. Overall, the proposed model is straightforward yet effective, providing accurate predictions when validated against a diverse set of 22 clay samples. The results demonstrate that the proposed model can be used for the design of clay calcination equipment.

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Appendix

See Figures 7 and 8 for results of XRD and DSC analyses.

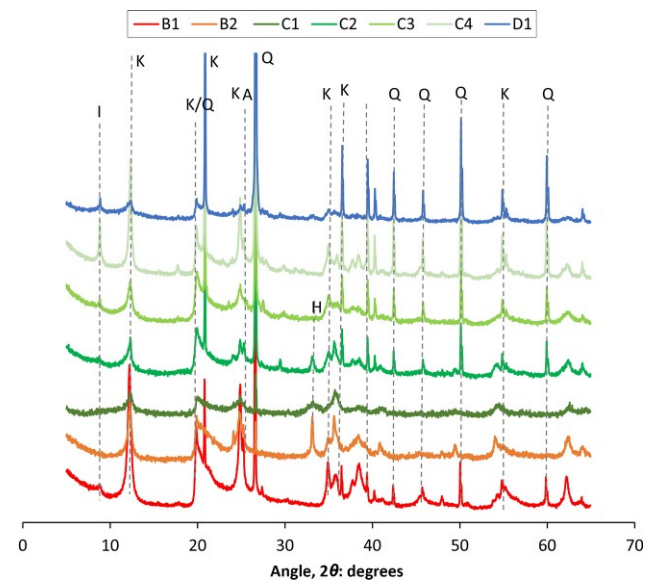


Figure 7. X-ray diffraction analysis (XRD) of raw clays

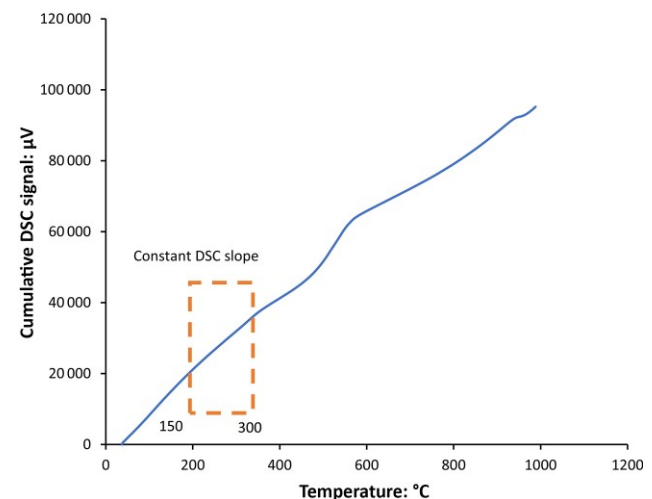


Figure 8. Cumulative differential scanning calorimetry (DSC) signal as a function of temperature

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