Article

Not peer-reviewed version

A Thermodynamic Screening Framework for Waste-Derived Raw Meals in Benchmarked Low-Temperature Clinker Production

Jeong-Hwan Bang , Bilguun Mend , Yong-Sik Chu *

Posted Date: 3 April 2026

doi: 10.20944/preprints202604.0245.v1

Keywords: low-temperature clinker; waste-derived raw meals; MSWI bottom ash; melt fraction; Fe-in-liquid; mineralized clinker; burnability

 doi:10.20944/preprints202604.0245.v1

Article

A Thermodynamic Screening Framework for Waste-Derived Raw Meals in Benchmarked Low-Temperature Clinker Production

Jeong-Hwan Bang , **Bilguun Mend** and **Yong-Sik Chu** *

Korea Institute of Ceramic Engineering and Technology, Climate and Energy R&D Group, Jinju, Republic of Korea
* Correspondence: yschu@kicet.re.kr

Abstract

This study develops a comparative screening framework for evaluating the feasibility of low-temperature clinker production using waste-derived raw meals under melt-phase and Fe-in-liquid constraints. The work addresses the need to connect two strategies for lower-emission cement manufacture that are often discussed separately: partial substitution of conventional raw materials with waste-derived inputs and reduction of clinker burning temperature through mineralized processing. A secondary-data analysis was conducted using selected open-access case studies and an open-access spreadsheet dataset, from which quantitative variables related to composition, process conditions, clinker formation, and cement performance were extracted and compared. The results show that feasibility depends not only on burning temperature, but also on major-oxide compatibility, minor-element constraints, burnability, clinker phase balance, melt-related indicators, and final cement performance. In the waste-substitution benchmark, MSWI bottom ash was compositionally feasible only within a limited substitution range controlled by Fe_2O_3 content. In the mineralizer benchmark, a reduction in burning temperature from 1450 °C to 1350 °C was found to be a practical benchmark for reduced-temperature clinker production, whereas further reduction to 1300 °C required stronger chemical assistance and led to performance penalties. Overall, the proposed framework distinguishes favorable, conditionally feasible, and constrained pathways and provides a basis for screening candidate systems before experimental validation.

Keywords: low-temperature clinker; waste-derived raw meals; MSWI bottom ash; melt fraction; Fe-in-liquid; mineralized clinker; burnability

---

1. Introduction

The cement industry is one of the most energy-intensive industrial sectors and a major source of CO_2 emissions [1,2]. In addition to process emissions from limestone decarbonation, conventional Ordinary Portland Cement (OPC) production requires high clinkering temperatures and large amounts of virgin raw materials [3,4]. These challenges have increased interest in production routes that can reduce thermal demand while promoting the use of secondary resources [5].

Two approaches are especially relevant in this context. The first is the partial replacement of conventional raw materials with waste-derived inputs containing useful clinker-forming oxides [6–10]. The second is the reduction of clinker burning temperature through mineralized processing and modified clinker chemistry. Although both strategies have been widely studied, they are often discussed separately rather than within a unified framework for evaluating low-temperature clinker feasibility.

Among potential waste-derived materials, municipal solid waste incineration bottom ash (MSWI BA) is of particular interest because it contains major oxides such as CaO, SiO_2, Al_2O_3, and Fe_2O_3 [11]. This makes MSWI BA a potentially useful secondary raw material for clinker production. However, its

 doi:10.20944/preprints202604.0245.v1

suitability cannot be assessed only from major-element composition. Minor elements, soluble salts, and compositional variability may also affect burnability, melt formation, clinker phase development, hydration behavior, and overall process stability [12].

Lowering clinker burning temperature is also challenging because clinkerization, particularly alite formation, depends strongly on high-temperature melt-assisted reactions. Previous studies have shown that mineralizers such as CaF_2 and $CaSO_4$ can improve burnability and enable clinker formation at reduced temperatures by modifying liquid-phase behavior [13]. In particular, burning at 1350 °C has been identified as a practical benchmark for reduced-temperature clinker production, whereas further reduction to 1300 °C generally requires stronger chemical assistance and may result in performance penalties [14,15].

Despite these advances, studies on waste-derived raw meals usually focus on substitution feasibility and cement performance, whereas studies on reduced-temperature clinker systems mainly emphasize burnability and mineralizer effects [16]. As a result, there remains a need for a comparative framework that links waste-derived raw meal feasibility with the key screening variables relevant to low-temperature clinker formation.

Therefore, this study develops a comparative screening framework for evaluating low-temperature clinker production using waste-derived raw meals under melt-phase and Fe-in-liquid constraints. Based on secondary-data analysis from selected open-access case studies and an open-access spreadsheet dataset, the study integrates compositional variables, process indicators, clinker-formation behavior, and cement performance into a common evaluation logic. The aim is to clarify the conditions under which reduced-temperature clinker production can be interpreted as favorable, conditionally feasible, or constrained.

2. Materials and Methods

2.1. Data Sources and Case-Study Selection

This study was conducted as a secondary-data analysis based on open-access literature and an open-access spreadsheet dataset. Three case studies were selected to build the screening framework: (i) an MSWI bottom ash study as a benchmark for waste-derived raw meal substitution, (ii) a CaF_2–$CaSO_4$ mineralizer study as a benchmark for reduced-temperature clinker formation, and (iii) an open-access spreadsheet dataset as the basis for compositional screening and melt-phase assessment. The selected sources and the variables extracted from each case study are summarized in Table 1.

Only quantitative variables directly relevant to clinker screening were extracted, including raw material chemistry, substitution level or mineralizer dosage, burning temperature, phase composition, free lime, and cement performance indicators. Microstructural and diffraction images reported in the original studies were not reproduced in this work; instead, only the numerical outputs derived from those analyses were used for comparison. This approach ensured a consistent dataset for evaluating the compositional and process variables associated with waste incorporation and low-temperature clinker production.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 3 April 2026 doi:10.20944/preprints202604.0245.v1

Table 1. Summary of open-access data sources and extracted variables used in this study.

Source	Material type	Study focus	Extracted variables
MSWI bottom ash case study [17]	Waste-derived raw meal substitute	Portland clinker production with secondary raw materials	Waste chemistry, substitution level, clinker phase composition, free lime, calorimetry, and compressive strength
CaF_2 + $CaSO_4$ mineralizer case study [18]	Mineralized low-temperature clinker system	Reduced-temperature clinker formation and burnability	F content, SO_3 content, free lime, clinker mineral composition, setting time, and compressive strength
Open-access spreadsheet dataset [19]	Thermodynamic screening dataset	Compositional screening and melt-phase assessment	Maximum C_3S, melt fraction, Fe in melt, screening thresholds, and compositional windows

Abbreviation: MSWI BA = municipal solid waste incineration bottom ash.

2.2. Comparative Data Extraction and Screening Variables

After the case studies were selected, the reported quantitative data were extracted and reorganized into a common comparative framework. Because the selected sources differed in material type, study purpose, and reporting style, the extracted data were not treated as a single merged dataset. Instead, they were harmonized at the level of screening variables so that the benchmark cases could be compared through a shared interpretive logic.

The variables retained for analysis were grouped into four categories: compositional variables, process variables, clinker-formation indicators, and cement performance indicators, as summarized in Table 2. This grouping was adopted to reflect the main stages through which low-temperature clinker feasibility can be interpreted, from raw-meal suitability to final cement behavior.

The compositional variables included the major oxides required for clinker formulation, together with reported minor elements that may influence melt formation, burnability, hydration behavior, and process stability. In this study, major oxides were used primarily to assess whether a waste-derived material could contribute to a clinker-compatible raw meal, whereas minor elements were treated as potential constraints that might offset this benefit under practical clinkering conditions.

The process variables included waste substitution level, mineralizer dosage, and burning temperature. These variables were selected because they define the operating conditions under which clinker formation was evaluated in the benchmark studies. In particular, waste substitution level was used to identify admissible incorporation ranges, while mineralizer dosage and burning temperature were used to compare conventional and reduced-temperature clinker production conditions.

The clinker-formation indicators included free lime, clinker phase composition, melt fraction, and Fe enrichment in the liquid phase. Free lime was used as the primary indicator of burnability and completeness of clinkerization. Phase composition, especially the balance between C_3S and C_2S, was used to assess whether reduced-temperature burning or waste incorporation remained compatible with acceptable Portland clinker characteristics. Melt-related variables were included to capture the thermodynamic and operability-related aspects of clinker formation, particularly the distinction between favorable liquid-phase development and excessive melt formation.

The performance indicators included setting time and compressive strength. These variables were treated as the final validation stage of the screening logic, because favorable clinker formation at the burnability or phase level does not necessarily guarantee acceptable cement behavior. For this reason, performance-related outputs were used to distinguish cases that remained practically feasible from those that became conditionally feasible or constrained.

This harmonized variable structure was used to compare the conditions under which waste incorporation remained compatible with acceptable clinker formation and cement performance. The extracted variables also served as the basis for the comparative screening logic developed in the following sections.

Table 2. Comparative screening variables extracted from the selected open-access case studies.

Variable group	Variable	Unit	Source case(s)	Relevance to screening
Composition	CaO, SiO_2, Al_2O_3, Fe_2O_3	wt.%	MSWI BA case; spreadsheet dataset	Major oxides required to evaluate whether a waste stream can be incorporated into a clinker raw meal while maintaining a feasible compositional window
Composition	Na, K, Cl, Zn, S, F	wt.% or mg/kg	MSWI BA case; mineralizer case	Minor elements potentially affecting melt formation, burnability, setting behavior, and operational constraints
Process	Waste substitution level	wt.%	MSWI BA case	Used to compare the feasible incorporation range and identify the limiting factor controlling the maximum waste dosage
Process	F content and SO_3 content in clinker	wt.%	Mineralizer case	Used to define benchmark conditions for reduced-temperature clinkering and equivalent burnability
Process	Burning temperature	°C	MSWI BA case; mineralizer case; low-burning clinker case	Core process variable used to compare conventional and reduced-temperature clinker formation

 doi:10.20944/preprints202604.0245.v1

Table 2. *Cont.*

Variable group	Variable	Unit	Source case(s)	Relevance to screening
Clinker formation	Free lime (f.CaO)	wt.%	Mineralizer case; MSWI BA case	Indicator of burnability and completeness of clinkerization
Clinker formation	Phase composition (C_3S, C_2S, C_3A, C_4AF)	wt.%	MSWI BA case; mineralizer case; spreadsheet dataset	Used to assess alite retention, belite formation, and compatibility with Portland clinker targets
Clinker formation	Melt fraction	wt.%	Spreadsheet dataset	Screening indicator for the compositional window associated with low-temperature clinker formation
Clinker formation	Fe enrichment in melt	wt.%	Spreadsheet dataset	Used as an operability-related screening variable for excessive liquid-phase enrichment
Performance	Setting time	min or h	Mineralizer case	Used to identify performance penalties associated with reduced burning temperature or excess mineralizer
Performance	Compressive strength	MPa	MSWI BA case; mineralizer case	Used to compare whether clinker modifications remain compatible with acceptable cement performance

Abbreviations: MSWI BA = municipal solid waste incineration bottom ash; f.CaO = free lime.

2.3. Comparative Screening Framework

The comparative screening framework developed in this study is presented in Figure 1. As shown in Figure 1, the evaluation proceeded through four sequential stages: compositional screening, process screening, clinker-formation screening, and performance screening. This structure was used to integrate the harmonized variables extracted from the selected open-access case studies into a single comparative assessment.

The first stage considered compositional feasibility. At this stage, the major oxides were used to determine whether a waste-derived material could contribute to a clinker-compatible raw meal, while the reported minor elements were treated as potential constraints because of their possible influence on melt formation, burnability, and hydration behavior. The second stage considered process-related variables, particularly waste substitution level, mineralizer dosage, and burning temperature, in order

 doi:10.20944/preprints202604.0245.v1

to compare conventional clinker production conditions with reduced-temperature cases reported in the literature.

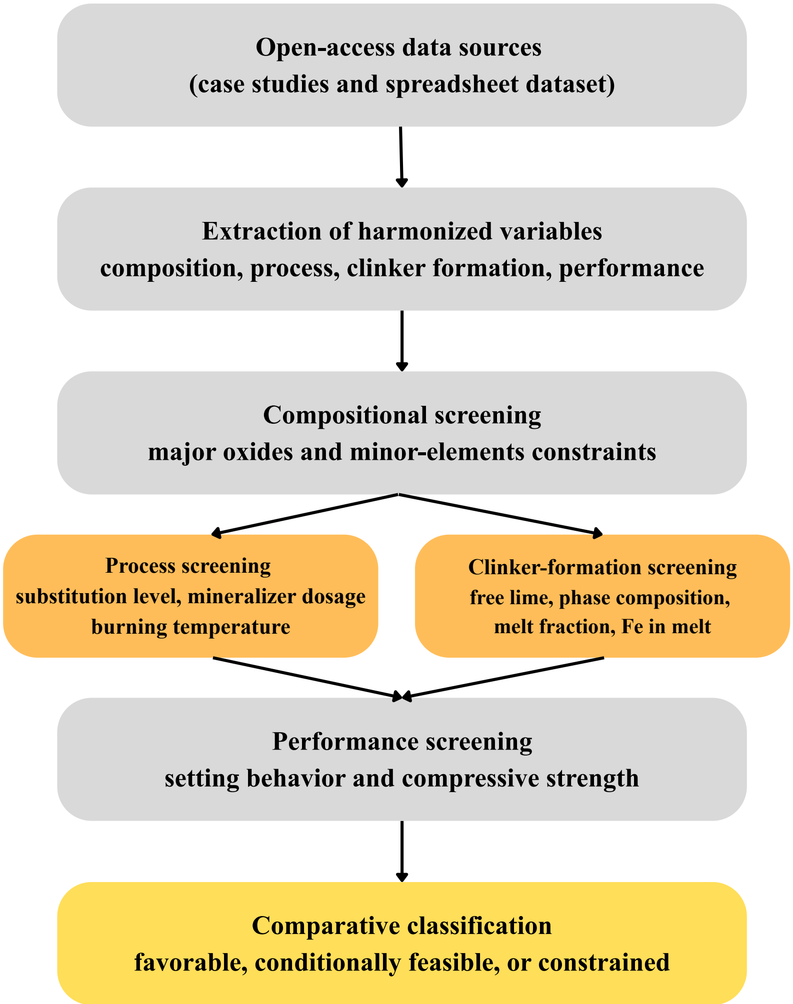

Figure 1. Comparative screening framework used to evaluate the feasibility of low-temperature clinker production from open-access case studies.

The third stage focused on clinker-formation indicators. Free lime was used as the primary indicator of burnability, while clinker phase composition was used to assess whether reduced-temperature burning remained compatible with acceptable alite retention. In parallel, the spreadsheet dataset was used to incorporate melt-related variables, particularly melt fraction and Fe enrichment in the liquid phase, so that compositions associated with excessive liquid-phase development could be distinguished from those more favorable for clinker formation.

The final stage considered cement performance. Setting behavior and compressive strength were used as practical validation criteria to determine whether the conditions identified as favorable at the clinkering stage also remained compatible with acceptable cement properties. On this basis, each case was interpreted as favorable, conditionally feasible, or constrained for low-temperature clinker production. The framework therefore provided a structured basis for comparing waste incorporation and reduced-temperature clinker formation across the selected open-access case studies.

 doi:10.20944/preprints202604.0245.v1

2.4. Benchmark Variables Adopted from the Reference Case Studies

To interpret the selected open-access case studies within a common screening framework, a set of benchmark variables was adopted from the literature. These variables were selected because they directly reflect the compositional, process, and performance conditions under which waste incorporation or reduced-temperature clinkering remained feasible.

For the MSWI bottom ash case, the benchmark variables included the substitution level, the limiting compositional factor controlling the maximum incorporation rate, the resulting clinker phase composition, and the reported cement performance. This case was used as the main benchmark for waste-derived raw meal feasibility because it explicitly linked raw meal substitution to clinker composition and compressive strength.

For the mineralizer case, the benchmark variables included fluorine content, sulfur trioxide content, burning temperature, free lime, clinker mineral composition, setting behavior, and compressive strength. This case was used as the benchmark for reduced-temperature clinker formation because it provided a direct comparison between conventional burning conditions and mineralized clinkers burned at lower temperatures but adjusted to achieve equivalent burnability.

The low-burning-temperature clinker case with shredded waste plastic was used as an additional process-level benchmark. In this case, the relevant variables included target mineral composition, estimated sintering temperature, kiln stability, and heat consumption. This source was used to support the interpretation of reduced-temperature clinker production under practical operating conditions.

These benchmark variables were not used to merge the three case studies into a single dataset. Instead, they were used to define reference ranges and comparison points for the screening logic developed in this study. Accordingly, the benchmark cases provided a structured basis for identifying whether low-temperature clinker feasibility was primarily constrained by bulk composition, minor-element effects, burnability, or final cement performance.

2.5. Scope and Limitations of the Secondary-Data Approach

The present study was conducted as a comparative secondary-data analysis based on selected open-access case studies and an open-access spreadsheet dataset. Accordingly, the objective was not to reproduce clinker synthesis experimentally, but to identify the compositional, process, and performance variables most consistently associated with feasible waste incorporation and reduced-temperature clinker formation across the available sources.

This approach has several limitations. First, the selected case studies were generated under different experimental conditions and for different purposes, and therefore the extracted variables are comparable only at an interpretive level. Second, the waste-derived material considered in the reference waste-substitution case, namely MSWI bottom ash, is known to be compositionally heterogeneous, which limits the direct transferability of the reported substitution range to other wastes or other ash sources. Third, the present study did not recalculate phase equilibria or generate new thermodynamic simulations, but relied on the screening variables already reported in the selected open-access sources. For this reason, the framework developed here should be understood as a comparative decision-support approach rather than a predictive model.

Another limitation is that the analysis focused on quantitative outputs extracted from the selected studies, such as phase composition, free lime, melt-related variables, and cement performance, whereas microstructural images and diffraction patterns were not used as primary evidence. This choice was made to maintain methodological consistency across sources and to restrict the comparison to variables that could be harmonized in numerical form.

Despite these limitations, the secondary-data approach remains useful for identifying benchmark ranges and screening logic for low-temperature clinker production. In particular, it enables direct comparison between waste-substitution feasibility, mineralizer-assisted temperature reduction, and melt-related screening criteria without introducing additional uncertainty from new laboratoryscale variability. The resulting framework is therefore intended as a structured basis for subsequent experimental validation rather than as a substitute for it.

3. Results and Discussion

3.1. Comparative Compositional Feasibility of Waste-Derived Inputs

The benchmark case studies show that the compositional feasibility of waste-derived inputs for clinker production depends on whether the material can supply the major oxides required for clinker formation without introducing excessive minor-element constraints. As shown in Figure 2 and summarized in Table 3, the MSWI bottom ash benchmark provides the clearest example of this dual requirement.

From the perspective of major-element chemistry, the MSWI bottom ash case indicates clear potential for use as a secondary raw material in clinker raw meals. The ash contains the principal clinker-forming elements, namely Ca, Si, Al, and Fe, which are necessary for the formation of the main Portland clinker phases. As illustrated in Figure 2, this compositional profile supports the interpretation of MSWI bottom ash not simply as a residue requiring disposal, but as a potentially useful input for partial substitution of virgin raw materials.

However, the same benchmark also shows that compositional feasibility cannot be evaluated on the basis of major oxides alone. The ash contains minor elements and soluble salts, including Na, Cl, and Zn, that may influence clinkerization behavior, melt formation, hydration, and process stability. This means that a waste-derived material may appear suitable at the bulk-oxide level while still introducing constraints that become important during burning or in the performance of the resulting cement. For this reason, the role of waste-derived inputs in the present framework is interpreted as inherently dual: they may contribute useful clinker-forming oxides, but they may also carry process-related and hydration-related risks.

The mineralizer benchmark provides a complementary comparison for understanding this balance. In that case, minor components such as fluorine- and sulfur-bearing additions were deliberately used to improve burnability and enable clinker formation at reduced temperature. This comparison is important because it shows that minor elements are not always unfavorable. Their effect depends on concentration, chemical form, and process context. Under controlled conditions, they may support low-temperature clinker formation; under less favorable conditions, they may instead narrow the feasible processing window or increase operability-related risks.

Taken together, the selected benchmark cases indicate that the compositional feasibility of waste-derived inputs for low-temperature clinker production should be interpreted as a preliminary screening outcome rather than a final judgment of suitability. A material can be considered compositionally feasible only when it satisfies two conditions simultaneously: first, it must contribute a useful proportion of the major clinker-forming oxides; second, its minor-element inventory must remain within a range that does not offset this benefit through excessive process, mineralogical, or performance-related penalties. Accordingly, compositional screening in the present study serves as the first boundary condition in the broader evaluation of low-temperature clinker feasibility, to be refined further by substitution limits, clinker-formation indicators, and cement performance.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 3 April 2026 doi:10.20944/preprints202604.0245.v1

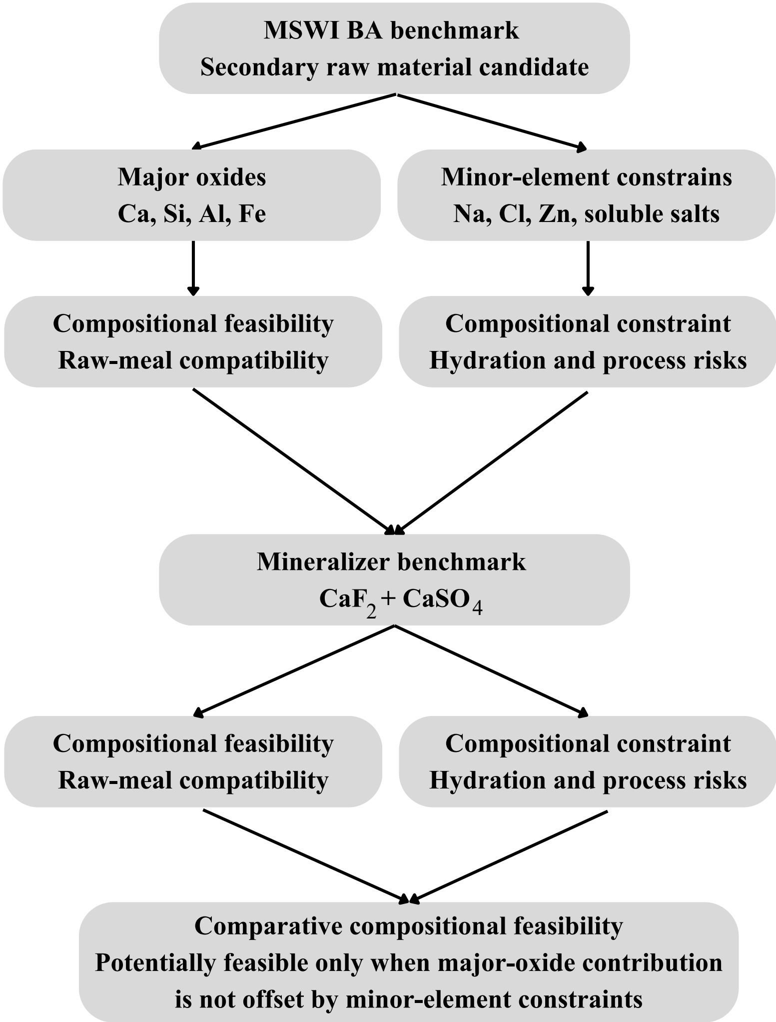

Figure 2. Comparative compositional feasibility map of the benchmark cases used in this study. The figure shows that the suitability of waste-derived inputs for low-temperature clinker production depends on the balance between the contribution of major clinker-forming oxides and the constraints introduced by minor elements. The MSWI bottom ash benchmark illustrates the dual role of waste-derived materials as both secondary raw-material sources and potential sources of process and hydration risks, whereas the mineralizer benchmark highlights the trade-off between improved burnability and operational constraints under reduced-temperature conditions.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 3 April 2026 doi:10.20944/preprints202604.0245.v1

Table 3. Benchmark compositional and process variables extracted from the selected case studies.

Case study	Benchmark variable	Value	Unit	Interpretation for screening
MSWI BA case	Maximum raw-meal substitution	12.4	wt.%	Upper incorporation limit for the selected French bottom ash under the targeted Portland clinker composition
MSWI BA case	Controlling factor of maximum substitution	Fe_2O_3	–	The limiting oxide controlling the admissible waste incorporation in the raw meal
MSWI BA case	Major oxides in bottom ash	Ca 18.91; Si 11.06; Al 5.57; Fe 9.45	wt.%	Confirms compositional suitability of the ash as a secondary raw material for clinker production
MSWI BA case	Key minor elements	Na 1.25; Cl 0.25; Zn 0.63	wt.%	Indicates potential constraints related to hydration retardation, mineralization effects, and process compatibility
MSWI BA case	Soluble chloride	2740	mg/kg	Indicates the presence of chloride as an operational constraint for waste-derived clinker systems
MSWI BA case	Soluble sulphate	5059	mg/kg	Indicates additional sulphate input relevant to clinker chemistry and process behavior

 doi:10.20944/preprints202604.0245.v1

Table 3. *Cont.*

Case study	Benchmark variable	Value	Unit	Interpretation for screening
Mineralizer case	Reference burning temperature	1450	°C	Benchmark conventional temperature for comparison with reduced-temperature clinker burning
Mineralizer case	Reduced burning temperature with equivalent burnability	1350	°C	Demonstrates a feasible 100 °C reduction under controlled mineralizer conditions
Mineralizer case	F content at 1350 °C	0.067	wt.%	Fluorine level required to match the burnability of the normal clinker burned at 1450 °C
Mineralizer case	SO_3 content at 1350 °C	2.2	wt.%	Sulfate level associated with improved burnability and reduced burning temperature
Mineralizer case	F content at 1300 °C	0.270	wt.%	Higher fluorine demand required to reach equivalent burnability at the lower temperature
Mineralizer case	C_3S content	56.1; 49.6; 49.1	wt.%	Alite content decreased as burning temperature was reduced from 1450 to 1350 and 1300 °C
Mineralizer case	C_2S content	21.2; 25.0; 25.0	wt.%	Belite content increased as burning temperature was reduced

Abbreviation: MSWI BA = municipal solid waste incineration bottom ash.

3.2. *Waste Substitution Limits and Controlling Factors*

The benchmark cases indicate that the admissible level of waste incorporation is controlled not by waste availability alone, but by the limiting compositional factor within the targeted clinker system. In the MSWI bottom ash case, two substitution levels were examined, namely 5 wt.% and the maximum feasible level of 12.4 wt.%. This upper limit was not arbitrary, but corresponded to the highest incorporation level that still satisfied the targeted Portland clinker composition.

The controlling factor in this case was the Fe_2O_3 content of the bottom ash. Once the substitution level exceeded 12.4 wt.%, the iron oxide supplied by the waste became greater than the amount required for the target clinker, and the resulting raw meal no longer matched the intended clinker formulation. This result shows that waste substitution limits should be interpreted as composition-dependent thresholds rather than as fixed values applicable to all waste streams.

 doi:10.20944/preprints202604.0245.v1

At the same time, the mineralizer benchmark provides an important comparison for understanding how such limits relate to low-temperature clinker feasibility. As shown in Figure 3, reduced-temperature clinker formation can be achieved when burnability is improved under controlled process conditions. However, the benchmark also shows that further reduction in temperature requires progressively stronger chemical assistance and may introduce performance penalties. This comparison suggests that the practical limit of waste substitution should not be evaluated only at the raw-meal level, but also in relation to the process conditions required to maintain acceptable clinker formation.

In the MSWI bottom ash case, the main clinker assemblage remained broadly comparable to that of the reference system, but the phase balance shifted as substitution increased. This indicates that the substitution limit was reached before the clinker system became fully incompatible, and was instead governed by the point at which one component exceeded the design tolerance of the targeted clinker. For this reason, waste substitution limits in the present study are treated as the first practical boundary condition within the broader screening framework for low-temperature clinker production.

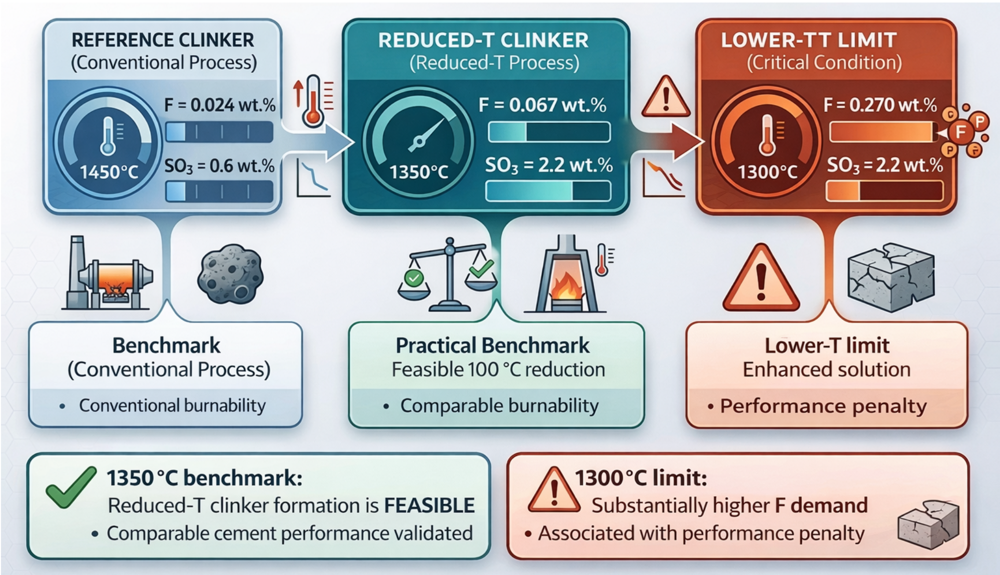

Figure 3. Reduced-temperature benchmark derived from the mineralizer case study. The figure summarizes the transition from conventional clinker burning at 1450 °C to reduced-temperature burning at 1350 °C and 1300 °C under increasing fluorine and sulfur trioxide contents. The benchmark indicates that comparable burnability can be achieved at 1350 °C under controlled mineralizer contents, whereas further reduction to 1300 °C requires substantially higher fluorine addition and is associated with lower cement performance.

3.3. Reduced-Temperature Benchmark from Mineralized Clinker Systems

The mineralizer case provides the main benchmark for interpreting reduced-temperature clinker formation in the present study. As shown in Figure 3, the conventional reference condition corresponded to clinker burning at 1450 °C, whereas the reduced-temperature cases were evaluated at 1350 °C and 1300 °C under progressively higher fluorine and sulfur trioxide contents. This benchmark is important because it demonstrates that low-temperature clinker formation is feasible, but only within a constrained compositional and process window.

The most relevant result is that equivalent burnability to the normal clinker burned at 1450 °C was achieved at 1350 °C when the fluorine content increased from 0.024 to 0.067 wt.% and the SO_3 content increased from 0.6 to 2.2 wt.%. In this case, the study explicitly used free lime as the burnability indicator, and the lower f.CaO confirmed that the mineralizer combination improved clinker formation at reduced temperature. Therefore, the 1350 °C case can be treated as the practical benchmark for a feasible 100 °C reduction in burning temperature.

However, the same benchmark also shows that the lower-temperature limit is more constrained. At 1300 °C, equivalent burnability was reached only when the fluorine content was increased further to 0.270 wt.%, while SO_3 remained around 2.2 wt.%. Although this condition reduced f.CaO to the target level, it did not provide the same overall clinker and cement behavior as the 1350 °C case. In particular, the 1300 °C clinker showed lower bulk density, indicating insufficient sintering, and the corresponding cement exhibited retarded setting and lower compressive strength. The clinker mineralogy supports the same interpretation. Compared with the normal clinker burned at 1450 °C, the mineralized clinkers burned at 1350 °C and 1300 °C had lower C_3S and higher C_2S contents. The reported Bogue mineral composition changed from 56.1 wt.% C_3S and 21.2 wt.% C_2S at 1450 °C to 49.6 wt.% C_3S and 25.0 wt.% C_2S at 1350 °C, and to 49.1 wt.% C_3S and 25.0 wt.% C_2S at 1300 °C. This indicates that, even when burnability is matched through mineralization, alite retention still decreases as the burning temperature is reduced.

Taken together, these results show that the mineralizer case does not support an unrestricted decrease in clinker burning temperature. Instead, it defines a practical reduced-temperature benchmark at 1350 °C, where burnability and cement performance remain broadly comparable to the conventional reference, and a more constrained lower-temperature limit at 1300 °C, where stronger mineralizer demand and poorer cement performance become evident. For the present screening framework, this means that 1350 °C should be interpreted as the most realistic benchmark for reduced-temperature clinker production, whereas 1300 °C represents a boundary condition rather than a generally favorable operating target.

3.4. Clinker-Formation Indicators for Screening Low-Temperature Feasibility

The selected benchmark cases show that low-temperature clinker feasibility should be evaluated from clinker-formation indicators rather than from burning temperature alone. As summarized in Table 4 and illustrated in Figure 4, the most relevant indicators in the present study were free lime, phase composition, and melt-related screening variables. Together, these parameters were used to distinguish between clinker systems that remained favorable under reduced-temperature conditions and those that became constrained by mineralogical or operability-related penalties.

Free lime was treated as the primary indicator of burnability. In both the MSWI bottom ash case and the mineralizer case, low residual free lime indicated that clinker formation was largely complete even when the raw meal composition or burning conditions were modified. However, acceptable burnability alone was not sufficient to define a favorable low-temperature condition. The phase balance of the produced clinker also had to remain compatible with Portland clinker behavior, particularly with respect to the retention of C_3S and the increase of C_2S.

This point is evident from the phase-composition data summarized in Table 4. In the MSWI bottom ash case, increasing waste substitution from OPC0 to OPC12.4 produced a progressive decrease in C_3S and an increase in C_2S, while the free-lime content remained low. A similar pattern was observed in the mineralizer benchmark, where the reduced-temperature clinkers burned at 1350 °C and 1300 °C showed lower C_3S and higher C_2S than the reference clinker burned at 1450 °C. These results indicate that reduced free lime does not necessarily imply full preservation of alite-rich clinker formation, and that phase balance must be considered together with burnability.

 doi:10.20944/preprints202604.0245.v1

Table 4. Comparative clinker-formation and performance outcomes used for screening.

Case	Condition	C_3S	C_2S	Free lime / CaO	Performance note	Screening interpretation
MSWI BA case	OPC0	76.14	12.27	0.21	Highest 1 d strength among the MSWI BA cements	Reference clinker benchmark
MSWI BA case	OPC5	74.01	15.21	0.05	Lower early-age strength, but limited medium-term penalty	Conditionally feasible waste substitution
MSWI BA case	OPC12.4	72.12	19.60	0.06	Stronger early-age retardation, but acceptable clinker formation	Upper-limit substitution under compositional constraint
Mineralizer case	1450 °C normal clinker	56.1	21.2	Reference burnability	Baseline cement performance	Conventional benchmark
Mineralizer case	1350 °C mineralized clinker	49.6	25.0	Equivalent to 1450 °C clinker	Cement performance remained broadly comparable	Favorable reduced-temperature benchmark
Mineralizer case	1300 °C mineralized clinker	49.1	25.0	Equivalent burnability achieved only with higher F content	Lower bulk density, retarded setting, and lower strength	Constrained lower-temperature limit

Abbreviation: MSWI BA = municipal solid waste incineration bottom ash. C_3S and C_2S are given in wt.%. Free lime / CaO values are reported as wt.% where available.

The melt-related indicators provide a third level of screening. As shown schematically in Figure 4, melt fraction and Fe enrichment in the liquid phase were interpreted as variables that help explain why some compositions remain favorable whereas others become conditionally feasible or constrained. In the screening logic adopted here, increased liquid-phase formation may improve burnability, but excessive melt development or excessive enrichment of specific elements in the melt may also increase operability-related risks and shift the clinker away from the desired compositional window.

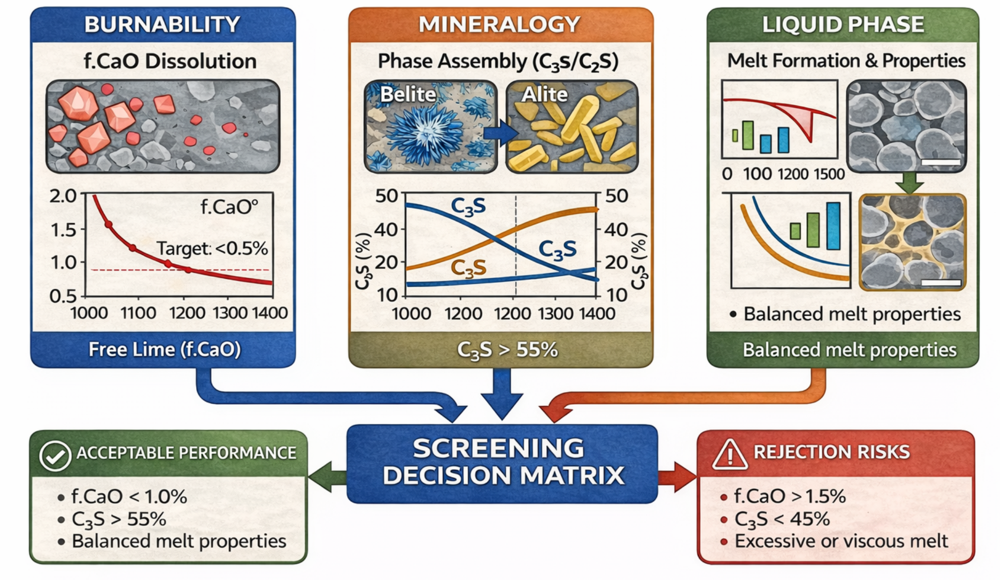

Figure 4. Clinker-formation indicators used for screening low-temperature feasibility. The figure summarizes the three main indicator groups considered in this study, namely free lime as a burnability indicator, phase composition in terms of C_3S retention and C_2S increase, and melt-related indicators including melt fraction and Fe enrichment in the liquid phase. Together, these indicators were used to distinguish favorable clinker formation from conditions associated with excessive alite loss or operability-related penalties.

Taken together, these indicators support a three-level interpretation of low-temperature feasibility. A clinker system was considered favorable when burnability improved without major loss of C_3S or evidence of excessive melt-related risk. It was considered conditionally feasible when clinker formation remained complete but the phase balance shifted toward lower alite content or higher belite content. Finally, it was considered constrained when acceptable burnability was achieved only at the expense of stronger mineralogical deviation or process-related penalties. On this basis, the clinker-formation indicators summarized in Table 4 and Figure 4 formed the core of the comparative screening framework developed in this study.

3.5. Cement Performance Implications

The benchmark cases show that clinker modifications associated with waste incorporation or reduced-temperature burning do not necessarily translate into unacceptable cement performance. Instead, the main effect appears at early age, whereas the medium- and later-age behavior remains closer to the reference system when clinker formation is still largely complete [20].

In the MSWI bottom ash case, the hydration curves of the three cement pastes remained broadly similar, but the setting of OPC0 started earlier than that of OPC5 and OPC12.4. This delay was attributed to the presence of trace elements and alkalis in the MSWI BA-based clinkers. The same case also showed that the early-age compressive strength decreased as the substitution level increased, whereas the difference became much less pronounced after 7 days. This indicates that the main penalty of waste incorporation was associated with short-term hydration and strength development rather than with a strong loss of overall cement performance [21].

A comparable interpretation can be drawn from the mineralizer benchmark. Cement burned at 1350 °C showed setting and strength behavior close to that of the reference cement burned at 1450 °C, despite the lower burning temperature. In contrast, the cement burned at 1300 °C showed retarded setting and lower compressive strength. This confirms that reduced-temperature clinker formation is feasible only within a bounded operating window, beyond which acceptable burnability is no longer sufficient to guarantee acceptable cement performance.

The low-burning-temperature clinker case with shredded waste plastic supports the same interpretation at the process scale. In that study, the strength development of the trial cement was slightly

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 3 April 2026 doi:10.20944/preprints202604.0245.v1

lower than that of the trial OPC, but the authors attributed this mainly to a lower-than-target C_3S content rather than to the use of the reduced-temperature route itself. This observation is important because it suggests that part of the apparent performance penalty may be explained by clinker composition control rather than by temperature reduction alone.

Taken together, these results indicate that cement performance should be interpreted as the final validation stage of the screening framework. Conditions that remain favorable at the clinker-formation stage can still become only conditionally feasible if they induce early-age retardation or reduce strength development. Conversely, when clinker composition remains sufficiently controlled, reduced-temperature production and moderate waste incorporation can remain compatible with acceptable cement performance [22,23].

3.6. Integrated Interpretation of Low-Temperature Clinker Feasibility

The comparative analysis indicates that low-temperature clinker feasibility should be interpreted as the combined outcome of compositional suitability, process conditions, clinker-formation behavior, and final cement performance rather than as the result of temperature reduction alone [24]. Across the selected benchmark cases, reduced-temperature clinker formation remained feasible only when the contribution of the waste-derived or mineralizing components improved burnability without causing excessive deviations in clinker phase balance or unacceptable performance penalties.

The MSWI bottom ash case shows that a waste-derived material can remain compatible with Portland clinker production when it supplies the required major oxides and does not prevent complete clinker formation. However, this case also demonstrates that increasing waste incorporation progressively shifts the clinker from a more alite-rich to a more belite-rich composition, while early-age hydration and strength become more sensitive to trace elements and alkalis [25]. Accordingly, this route can be interpreted as conditionally feasible: clinker formation remains acceptable, but the compositional and performance margins become narrower as the substitution level increases.

The mineralizer benchmark defines the practical reduced-temperature window more clearly. In this case, the 1350 °C condition can be interpreted as favorable because equivalent burnability was achieved relative to the conventional 1450 °C clinker while cement performance remained broadly comparable. By contrast, the 1300 °C condition should be interpreted as constrained. Although equivalent burnability was reached through higher fluorine addition, the resulting clinker showed lower bulk density, retarded setting, and lower compressive strength, indicating that the lower temperature could not be considered broadly favorable under the reported conditions [26].

Taken together, these benchmark cases support a three-level interpretation of low-temperature clinker feasibility. A condition is favorable when reduced-temperature burning or waste incorporation improves or preserves burnability while maintaining acceptable clinker phase balance and cement performance [27]. It is conditionally feasible when clinker formation remains complete but the mineralogical shift or early-age performance penalty becomes more pronounced. It is constrained when acceptable burnability is obtained only through stronger chemical assistance or when the final clinker and cement properties deviate too far from the conventional reference.

On this basis, the present study identifies 1350 °C as the most realistic benchmark for low-temperature clinker production within the selected literature, whereas further reduction toward 1300 °C should be treated as a boundary condition rather than a general target. Similarly, moderate waste substitution can be considered feasible when the major-oxide contribution is useful and the minor-element inventory remains manageable, but the admissible range must be defined by the limiting compositional factor and validated against clinker-formation and performance indicators. The integrated screening framework developed here therefore supports low-temperature clinker design not by proposing a single universal route, but by distinguishing favorable, conditional, and constrained pathways on a comparative basis.

4. Conclusions

This study proposed a comparative screening framework for assessing low-temperature clinker feasibility using open-access case studies and an open-access spreadsheet dataset. The results show that feasibility depends not only on burning temperature, but also on composition, burnability, clinker phase balance, and cement performance.

The MSWI bottom ash benchmark showed that waste-derived materials can be used as secondary raw materials when they provide the major clinker-forming oxides. However, the admissible substitution level was limited by Fe_2O_3 content, and increasing substitution shifted the clinker toward lower C_3S and higher C_2S contents, with a corresponding reduction in early-age strength.

The mineralizer benchmark showed that a practical reduction in burning temperature from 1450 to 1350 °C is feasible when F and SO_3 contents are adjusted to achieve equivalent burnability. In contrast, further reduction to 1300 °C required higher fluorine addition and resulted in retarded setting and lower compressive strength.

The most useful screening indicators were free lime, phase composition, melt-related variables, and cement performance. Low residual free lime alone was not sufficient to define a favorable low-temperature route, because acceptable burnability could still be accompanied by reduced alite retention or performance penalties.

Overall, the selected literature supports a three-level interpretation of low-temperature clinker feasibility: favorable, conditionally feasible, and constrained. Within this framework, 1350 °C can be regarded as the most realistic benchmark for reduced-temperature clinker production, while 1300 °C should be treated as a lower boundary condition. The proposed framework can therefore serve as a basis for screening waste-derived and mineralized clinker systems before experimental validation.

Author Contributions: Conceptualization, J.-H.B and B.M.; methodology, B.M.; software, B.M.; validation, B.M. and Y.-S.C.; formal analysis, J.-H.B.; investigation, J.-H.B.; writing—original draft preparation, J.-H.B. and B.M; writing—review and editing, B.M.; visualization, J.-H.B.; supervision, Y.-S.C.; project administration,Y.-S.C.; funding acquisition, Y.-S.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Technology Innovation Program (RS-2024-00438915, Development of technology for continuous process of low-temperature sintering clinkers and high efficiency of preheating and cooling processes) funded by the Ministry of Trade, Industry & Resources (MOTIR, Korea).

Data Availability Statement: The data presented in this study were derived from publicly available resources in the public domain, namely: Kleib et al. [17], Telschow [18], and Chabayashi et al. [19].

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

MSWI BA	Municipal solid waste incineration bottom ash
OPC	Ordinary Portland cement
f.CaO	Free lime
C_3S	Tricalcium silicate (alite)
C_2S	Dicalcium silicate (belite)
C_3A	Tricalcium aluminate
C_4AF	Tetracalcium aluminoferrite
CO_2	Carbon dioxide
Fe_2O_3	Iron(III) oxide
SO_3	Sulfur trioxide

References

1. Begum, R. A.; Sohag, K.; Abdullah, S. M. S.; Jaafar, M. CO2 Emissions, Energy Consumption, Economic and Population Growth in Malaysia. Renewable and Sustainable Energy Reviews 2015, 41, 594–601. https://doi.org/10.1016/j.rser.2014.07.205.

2. Ozturk, I.; Acaravci, A. CO2 Emissions, Energy Consumption and Economic Growth in Turkey. Renewable and Sustainable Energy Reviews 2010, 14 (9), 3220–3225. https://doi.org/10.1016/j.rser.2010.07.005.
3. Kupwade-Patil, K.; De Wolf, C.; Chin, S.; Ochsendorf, J.; Hajiah, A. E.; Al-Mumin, A.; Büyüköztürk, O. Impact of Embodied Energy on Materials/Buildings with Partial Replacement of Ordinary Portland Cement (OPC) by Natural Pozzolanic Volcanic Ash. Journal of Cleaner Production 2018, 177, 547–554. https://doi.org/10.1016/j.jclepro.2017.12.234.
4. Karadumpa, C. S.; Pancharathi, R. K. Study on Energy Use and Carbon Emission from Manufacturing of OPC and Blended Cements in India. Environmental Science and Pollution Research 2023, 31 (4), 5364–5383. https://doi.org/10.1007/s11356-023-31593-3.
5. Mend, B.; Lee, Y.; Kwon, D.-Y.; Kim, J.-H. J.; Chu, Y.-S. Calcium Fluoride as an Efficient Mineralizer for Low-Temperature Portland Cement Clinkering: A Mechanistic Mini Review. Frontiers in Materials 2026, 13. https://doi.org/10.3389/fmats.2026.1779429.
6. Julphunthong, P.; Joyklad, P. Utilization of Several Industrial Wastes as Raw Material for Calcium Sulfoaluminate Cement. Materials 2019, 12, 3319. https://doi.org/10.3390/ma12203319
7. Sarsenbayev, B.; Murtazaev, S.-A.; Salamanova, M.; Kuldeyev, E.; Saidumov, M.; Sarsenbayev, N.; Auyesbek, S.; Sauganova, G.; Abduova, A. Utilization of Anthropogenic and Natural Waste to Produce Construction Raw Materials. Sustainability 2025, 17, 2791. https://doi.org/10.3390/su17072791
8. Oh, D.; Noguchi, T.; Kitagaki, R.; Choi, H. Proposal of Demolished Concrete Recycling System Based on Performance Evaluation of Inorganic Building Materials Manufactured from Waste Concrete Powder. Renewable and Sustainable Energy Reviews 2021, 135, 110147. https://doi.org/10.1016/j.rser.2020.110147.
9. He, Z.; Zhu, X.; Wang, J.; Mu, M.; Wang, Y. Comparison of CO2 Emissions from OPC and Recycled Cement Production. Construction and Building Materials 2019, 211, 965–973. https://doi.org/10.1016/j.conbuildmat.2019.03.289.
10. Mend, B.; Lee, Y.; Bang, J.-H.; Kim, J.-H. J.; Chu, Y. S. Performance and Environmental Assessment of Portland Cement Incorporating Waste-Derived Ferrous Sulfate as a Gypsum Substitute: A Case Study. Case Studies in Construction Materials 2026, e05909. https://doi.org/10.1016/j.cscm.2026.e05909.
11. Panda, S.; Pradhan, M.; Panigrahi, S. K. Sustainable Development of Ternary Binder-Based Mortar Using OPC, GGBFS, and Coal Bottom Ash. Construction and Building Materials 2025, 496, 143862. https://doi.org/10.1016/j.conbuildmat.2025.143862.
12. Lee, B. Y.; Jeon, S.-M.; Geun Cho, C.; Kim, H.-K. Evaluation of Time to Shrinkage-Induced Crack Initiation in OPC and Slag Cement Matrices Incorporating Circulating Fluidized Bed Combustion Bottom Ash. Construction and Building Materials 2020, 257, 119507. https://doi.org/10.1016/j.conbuildmat.2020.119507.
13. Mend, B.; Lee, Y.; Kim, J.-H. J.; Chu, Y.-S. Reducing Cement Clinker Sintering Temperature Using Fluorine-Containing Semiconductor Waste. Materials 2025, 18 (17), 4202. https://doi.org/10.3390/ma18174202.
14. Guo, Z.; Yao, X.; Duan, S.; Sang, Y.; Ma, Z.; Guo, Y.; Cheng, F. Effect of Calcium Source on the Phase Evolution and Hydration of Belite-Ye'elimite-Ferrite Clinker: Replacing CaCO3 with CaSO4. Construction and Building Materials 2026, 506, 144966. https://doi.org/10.1016/j.conbuildmat.2025.144966.
15. Mend, B.; Lee, Y.; Bang, J.-H.; Chu, Y.-S. Environmental Benchmarking for Sustainable Clinker Production: A Harmonized Cradle-to-Gate Life Cycle Assessment Using Real Industrial Data. Sustainability 2026, 18, 2867. https://doi.org/10.3390/su18062867
16. Bartonickova, E.; Ptacek, P.; Novotny, R.; Palovcik, J.; Masilko, J.; Svec, J.; Sedlacik, M.; Koplik, J.; Stanek, T.; Hemzal, D. Hydration Kinetics of C3A: Effect of Lithium, Copper and Sulfur-Based Mineralizers. Journal of Thermal Analysis and Calorimetry 2024, 150 (2), 1119–1135. https://doi.org/10.1007/s10973-024-13525-6.
17. Kleib, J.; Aouad, G.; Khalil, N.; Zakhour, M.; Abriak, N.-E.; Benzaazoua, M.; Damidot, D. Production of Portland cement clinker from French Municipal Solid Waste Incineration Bottom Ash. Case Stud. Constr. Mater. 2021, 15, e00629. https://doi.org/10.1016/j.cscm.2021.e00629.
18. Telschow, S. 2012. Clinker Burning Kinetics and Mechanism. Ph.D. Thesis, Technical University of Denmark (DTU), Department of Chemical and Biochemical Engineering. Available at: https://backend.orbit.dtu.dk/ws/portalfiles/portal/51216918/PhD-thesis-Samira-Telschow..PDF.
19. Chabayashi, T.; Nagata, H.; Matsui, Y.; Atarashi, D. Burning Test of the Low Burning-Temperature Type Clinker by Actual Kiln for the Purpose of CO_2 Reduction and Properties of the Cement. Cement Science and Concrete Technology 2022, 76, 60–67. https://doi.org/10.14250/cement.76.60

 doi:10.20944/preprints202604.0245.v1

20. Mend, B.; Lee, Y.; Bang, J.-H.; Chu, Y.-S. Environmental Benchmarking for Sustainable Clinker Production: A Harmonized Cradle-to-Gate Life Cycle Assessment Using Real Industrial Data. Sustainability 2026, 18, 2867. https://doi.org/10.3390/su18062867
21. Łaźniewska-Piekarczyk, B.; Smyczek, D. Valorization of Mineral Wool Waste as a Pozzolanic Supplementary Cementitious Material—Comparative Reactivity in Portland and Calcium Sulfoaluminate Systems. Sustainability 2026, 18, 3366. https://doi.org/10.3390/su18073366
22. Kryvenko, P.; Rudenko, I.; Konstantynovskyi, O.; Onatii, V. High Temperature Resistance of Fly Ash-Enhanced Alkali Activated Portland Cement Mortar: Microstructural Evolution and Strength Retention. Appl. Sci. 2026, 16, 2676. https://doi.org/10.3390/app16062676
23. Li, J.; Li, B.; Yuan, B.; Yang, K.; Chen, W. Effect of Fe2O3 Content on Clinkerization of Low Calcium Carbonatable Belite-Rankinite Clinker. Construction and Building Materials 2025, 463, 140078. https://doi.org/10.1016/j.conbuildmat.2025.140078.
24. Kleib, J.; Aouad, G.; Abriak, N.-E.; Benzerzour, M. Production of Portland Cement Clinker from French Municipal Solid Waste Incineration Bottom Ash. Case Studies in Construction Materials 2021, 15, e00629. https://doi.org/10.1016/j.cscm.2021.e00629.
25. Li, Y.-M.; Wu, X.-Q.; Wang, L.-J.; Li, R.-Q.; Huang, T.-Y.; Wen, X.-Q. Comparative Study on Utilization of Different Types of Municipal Solid Waste Incineration Bottom Ash for Clinker Sintering. Journal of Material Cycles and Waste Management 2020, 22 (6), 1828–1843. https://doi.org/10.1007/s10163-020-01067-6.
26. Clavier, K. A.; Paris, J. M.; Ferraro, C. C.; Bueno, E. T.; Tibbetts, C. M.; Townsend, T. G. Washed Waste Incineration Bottom Ash as a Raw Ingredient in Cement Production: Implications for Lab-Scale Clinker Behavior. Resources, Conservation and Recycling 2021, 169, 105513. https://doi.org/10.1016/j.resconrec.2021.105513.
27. Žibret, L.; Andrej Ipavec; Dolenec, S. Microstructural Characteristics of Belite–Sulfoaluminate Cement Clinkers with Bottom Ash. Construction and Building Materials 2022, 321, 126289–126289. https://doi.org/10.1016/j.conbuildmat.2021.126289.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.