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When Do Slag Viscosity Models Fail? A Critical Review of Empirical, Structural, and Thermodynamic Approaches for Multicomponent Melts

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Abstract

Reliable slag-viscosity predictions require agreement between the modeled physical state and the melt's chemistry, temperature, oxidation conditions, and phase constitution. This critical review examines empirical and semi-empirical correlations, network-structure descriptions, thermodynamic/CALPHAD-coupled models, and machine-learning approaches for multicomponent oxide systems. This review conceptually evaluates a curated bibliography of 145 publications across measurement reliability, composition–structure relations, model transferability, partial crystallization, and industrial consequences. Rather than assigning a universal accuracy ranking from incompatible datasets, the synthesis distinguishes interpolation in homogeneous liquids from extrapolation to new chemistry and effective-viscosity prediction in solid–liquid mixtures. The main limitations are insufficient redox-state characterization, differences between nominal and measured composition, uncontrolled phase precipitation, inconsistent experimental methods, and leakage between training and validation datasets. We propose a domain-based verification framework that combines phase screening, model-specific validation, uncertainty reporting, and targeted experimental confirmation. The resulting approach connects predictive credibility to engineering decisions without assuming that higher mathematical complexity necessarily improves reliability.

Keywords: molten slag viscosity; oxide melt structure; CALPHAD; phase precipitation; model applicability; uncertainty quantification

Highlights

- Model ranking depends on the chemical, redox, thermal, and phase domain.
- Liquid viscosity and suspension effective viscosity require separate models.
- Reported fit accuracy cannot substitute for independent compositional validation.
- A decision framework links model uncertainty with targeted measurements.

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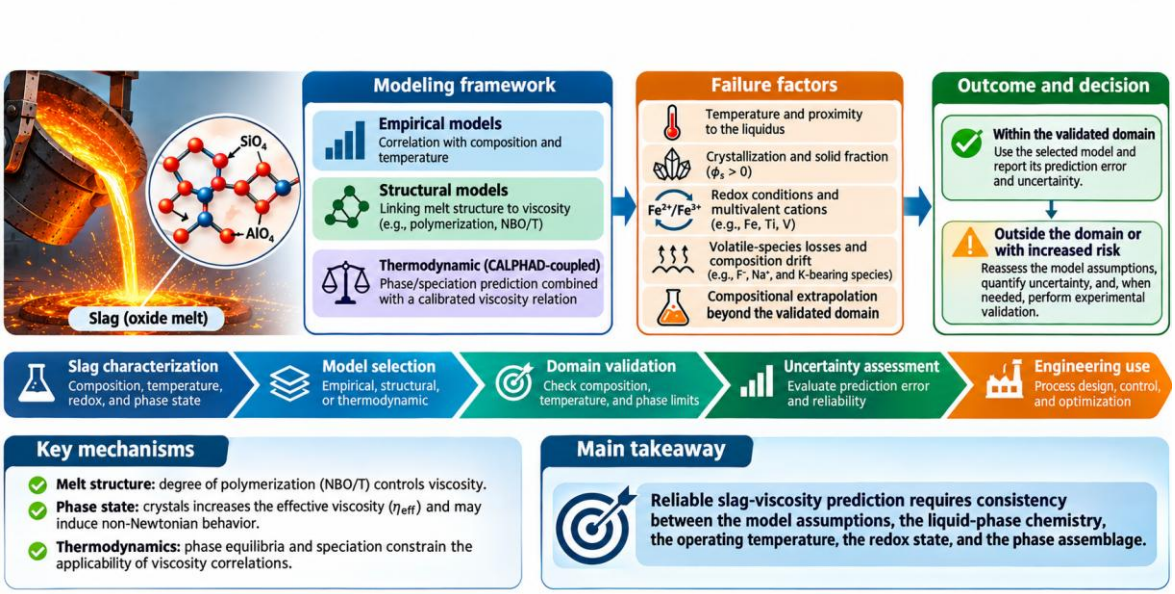
Graphical Abstract



1. Introduction

In furnace engineering, molten-slag viscosity affects drainage, bubble residence, interfacial momentum transfer, metal-droplet settling, inclusion removal, and heat transfer. Its influence varies by process: drainage depends mainly on flow resistance, while droplet settling also depends on density contrast and interfacial effects. Thus, a modest prediction error may be tolerable in one operation but consequential in another.

Industrial slags rarely fit the narrow composition–temperature ranges used to develop classical equations. Their oxide proportions vary with feed, refractory dissolution, redox conditions, volatilization, and phase separation. A model validated for homogeneous liquids may not apply to cooling, particle-laden slags. Distinguish the remaining liquid's viscosity from the mixture's apparent or effective viscosity.

This review asks when predictions stop being transferable, not which equation has the lowest error in its calibration database. Figure 1 links composition to process outcomes. Tables 2 and 3 summarize requirements for valid measurement and model comparison, while Figures

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2–4 show how model complexity relates to extrapolation, phase change, and industrial selection.

Figure 1 brings together composition, structural connectivity, phase equilibria, and rheological response. The links represent dependencies to be tested, not an assumption that each property can be computed from the preceding one without calibration.

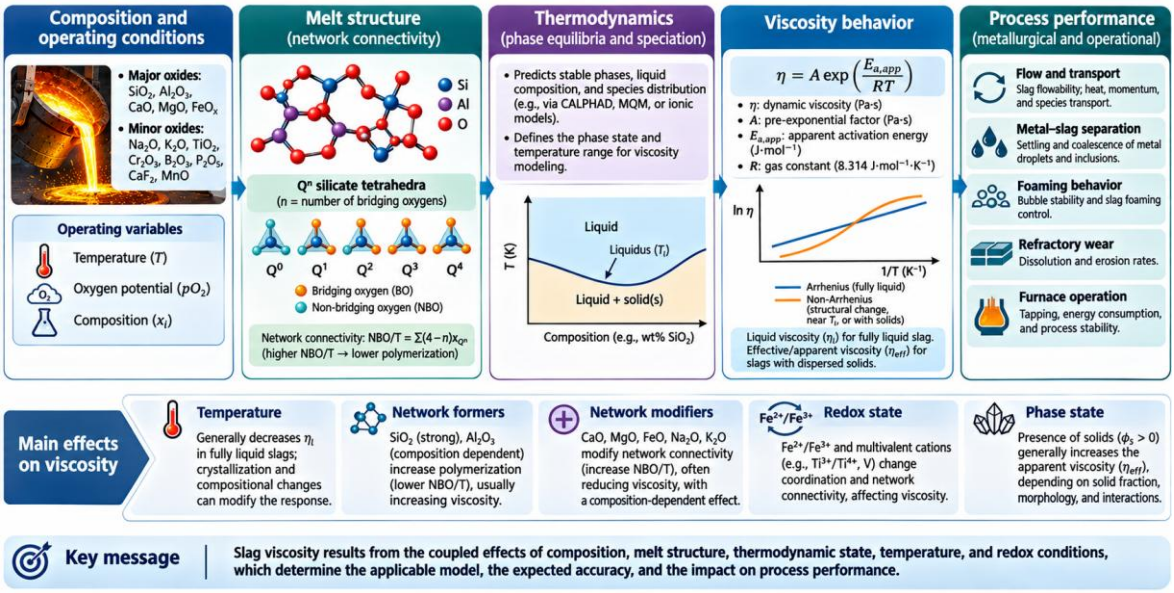

Figure 1. Coupled influences of composition, melt structure, phase state, and temperature on slag viscosity and process behavior.
Note. Original conceptual illustration prepared for this review; scientific content is synthesized from the references discussed in the accompanying text.

This distinction matters in a plant: a composition change can alter the equilibrium liquid fraction at the same time as it alters the viscosity of the remaining liquid. The two effects should be evaluated separately.

This article is a critical narrative review, not a registered systematic review. Section 2 details its analytical approach, the scope of the supplied 145-record bibliography, and the limitations of the evidence synthesis. Accordingly, the comparisons distinguish documented mechanisms and applicability conditions from numerical performance claims that would require harmonized raw data and executable model implementations.

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2. Review Methodology

2.1. Review Design and Research Question

The review adopts a critical narrative design to examine when viscosity predictions for multicomponent oxide slags cease to be physically or statistically transferable. The guiding question is whether a given model represents the material's actual chemical, thermal, redox, and phase state for which an engineering prediction is required. The review does not aim to estimate a pooled model error or to rank equations universally.

2.2. Bibliographic Corpus and Search Transparency

The starting material was an author-supplied, curated bibliography reported to contain 145 records. Its compilation provenance beyond that supplied collection, original databases and search strings, search dates, initial retrieval and duplicate counts, language restrictions, and formal eligibility decisions were not documented in the material available for this review. The years represented by the supplied references do not establish a prospective publication-date filter. The present review therefore treats this collection as a purposively assembled narrative source base, not as the yield of a reproducible systematic search. Correspondence of the manuscript reference list to the reported 145-record source collection cannot be fully certified without the underlying versioned source list; the count of reference entries in the revised manuscript is reported separately below. Consequently, the synthesis does not claim exhaustive coverage or estimate the prevalence of a failure mechanism across the full published literature. The current bibliography contains 145 recognizable year-tagged entries under References (a document-level count, not a verified match to the supplied source collection).

2.3. Scope and Relevance Criteria

For critical interpretation, a study is relevant when it addresses at least one of the following: experimental viscosity determination and associated metadata; composition–structure–viscosity relationships; prediction methods and their parameterization; phase

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equilibria, oxidation state, or partial crystallization affecting the modeled state; validation and uncertainty; or implications for metallurgical operation. Sources are interpreted within the domains actually investigated. This thematic framework describes the scope of the synthesis; it should not be mistaken for a retrospectively documented article-by-article eligibility screen.

2.4. Critical Appraisal and Evidence Organization

For auditability, Table 1 provides a targeted source-to-claim matrix of central illustrative references. The source types, nominal chemical systems, and declared contributions are inferred from the bibliographic descriptions and their use in the present narrative; they are not presented as a new full-text extraction audit, proof of independent validation, or a census of the corpus. “Not established” explicitly means that the available bibliographic information does not substantiate the corresponding level of evidence. Contrasting reports are discussed by their composition, redox, thermal, and phase-state assumptions where these are identifiable, without assigning numerical weights to studies.

Evidence is examined along five complementary axes: (i) reliability of the measured state, including post-test chemistry, temperature, atmosphere, thermal history, and viscometry; (ii) physical consistency between a model and homogeneous-liquid or multiphase rheology; (iii) coverage of chemical compositions, redox conditions, and phase fields; (iv) independence of calibration and validation evidence, with attention to shared experimental campaigns and data leakage; and (v) engineering significance of uncertainty for the decision being considered. Claims about mechanisms are distinguished from demonstrated out-of-domain predictive accuracy. Tables 1–4 organize measurement requirements, model families, validation levels, and the liquid-versus-suspension distinction; Figures 1–4 provide conceptual syntheses and decision guidance rather than primary experimental results.

Table 1. Targeted evidence-to-claim audit of illustrative references.

Reference	Source / system	State / conditions	Validation evidence	Appraisal axis	Supported role / limit

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Kim et al. (2021a)	Model; Fe oxide silicates	Fe-saturation regime	Not established here	Redox / domain	Separately parameterized Fe-saturated condition
Kim et al. (2021b)	Model; FeO–Fe_2O_3 silicates	Iron oxide speciation	Not established here	Redox / domain	Fe valence-aware model; not an experimental redox benchmark
Xu et al. (2015)	Experimental; CaO–MgO(–Al_2O_3)–SiO_2	Liquid and solid–liquid mixtures	Not established here	Phase / rheology	Directly addresses mixtures; no universal exponent established
W. Yan et al. (2019)	Mould-flux study; CaO–Al_2O_3–B_2O_3–CaF_2	Casting flux chemistry	Not established here	Process domain	Direct flux-viscosity relevance; heat flux not verified
Wang, W., et al. (2016)	Review; high-Al steel mold fluxes	Casting process	Secondary synthesis	Process domain	Casting-specific background; not a standalone validation
Jia et al. (2026)	ML; steelmaking slags	Dataset-specific liquid viscosity	Independence not established	Validation / transfer	Interpretability; not solid-particle exponent evidence
Kondratiev et al. (2012)	Model; fully liquid slags	Homogeneous liquid	Not established here	Physical consistency	Quasi-chemical approach excludes direct suspension calibration
Laabs et al. (2022)	Experimental comparison; coal ash slags	Viscometry setups	Cross-setup context; details unchecked	Measurement	Method sensitivity in viscosity measurement
Z. Yan et al. (2019)	Model; aluminosilicate slag	Structure-based liquid model	Not established here	Model / validation	Structural model, distinct from Yan W mold-flux study

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The evidence matrix records illustrative source-to-claim links and explicitly distinguishes bibliographic indications from independently verified experimental findings. It is not an exhaustive screening result or an independent benchmark.

2.5. Synthesis Method and Limitations

The synthesis is qualitative and mechanism-oriented. Contradictory findings are interpreted in relation to differences in composition, phase state, oxidation conditions, measurement protocol, and validation domain, rather than averaged into a single performance score. No new experiments, common-data recalibration, meta-analysis, or independent computational benchmark was performed. Consequently, the review can identify recurring failure mechanisms and propose a domain-based verification procedure. Still, it cannot assign comparative numerical accuracy to individual implementations without consistent datasets and model specifications. The absence of a fully documented search and screening record also limits claims of bibliographic completeness and reproducibility.

3. Physical Meaning of Slag Viscosity

For a Newtonian liquid, viscosity η is the proportionality constant between shear stress τ and shear rate $\dot{\gamma}$: $\tau = \eta\dot{\gamma}$. This definition describes a single-phase liquid under conditions where a constant proportionality is physically defensible. The strong temperature dependence of oxide-melt viscosity often motivates an Arrhenius-type approximation, $\ln \eta = \ln A + E_a/(RT)$, where A is a prefactor, E_a is an apparent activation energy, R is the universal gas constant, and T is the absolute temperature. The slope need not remain constant across broad temperature intervals or phase transitions.

The liquidus temperature locates an equilibrium boundary, but does not determine the amount or morphology of solid material present during a specific thermal history. Slow cooling, thermal gradients, nucleation barriers, and variable residence times can produce different solid fractions at an identical nominal temperature. The commonly reported critical

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viscosity or break temperature therefore has an operational and method-dependent meaning; it is not interchangeable with the equilibrium liquidus.

Once crystals, undissolved feed, or entrained bubbles occupy appreciable volume, the measured resistance belongs to a suspension rather than the pure liquid. Shear-rate dependence, yield-like behavior, and time-dependent aggregation can appear. Comparing such a measurement with a homogeneous-liquid model without identifying the phase state confounds a constitutive-law discrepancy with a difference in the material being measured.

3.1. Composition–Structure–Viscosity Relationships

Silica-rich oxide melts can form interconnected tetrahedral networks, while additions of basic oxides commonly alter the population of bridging and non-bridging oxygens. The size of this effect depends on local charge balance and the other cations present. Alumina is particularly nontrivial: it can be incorporated into a charge-balanced network or assume different structural roles as chemistry changes. Accordingly, a mass-based basicity index cannot uniquely determine network connectivity or viscosity.

Interpretations based on Q^n species and non-bridging oxygen per tetrahedron (NBO/T) provide a useful molecular description for silicate tetrahedra. Still, the correspondence between a structural descriptor and transport resistance depends on how that descriptor was established. Raman spectroscopy, nuclear magnetic resonance, and molecular simulations have distinct response functions and uncertainties. Neither a single spectral band assignment nor one nominal NBO/T value should be assumed to encode all structural information in a complex melt.

Iron, titanium, and chromium oxides require attention beyond their total oxide content. Their oxidation states depend on oxygen potential and temperature, and can affect both structural associations and phase stability. Alkali oxides, fluoride-bearing compounds, borate, and phosphate modify the local bonding environment through mechanisms that are not necessarily additive. Compositions near primary crystalline phase fields are especially

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sensitive because an oxide addition may change the liquid structure and simultaneously promote or suppress precipitation.

The resulting picture is conditional rather than monotonic: the same compositional change can have a different apparent effect in separate base systems. Model transfer is most defensible when both composition and phase assemblage remain near the domain used for parameterization. A successful regression against basicity should therefore be treated as a restricted empirical observation, not as evidence that basicity is an adequate state variable for every industrial slag. The distinct influence of MgO and K_2O in particular slag families illustrates why composition-specific validation remains necessary (Xing, Pang, Zheng, et al., 2020).

Network-based interpretations must distinguish network-former concentration from its coordination and charge-balancing environment. Measurements across different oxide families cannot be arranged on a single basicity axis without losing information about local connectivity and temperature. (Choi et al., 2021; Feng et al., 2020; Haghdani et al., 2022; Kim & Sohn, 2014; Kim & Park, 2022).

Raman, NMR, and related structural descriptors are valuable when they independently constrain a model, but a spectroscopic index inferred from the same composition used for viscosity fitting is not independent validation. (Li et al., 2015; Li et al., 2020; Mills, 2011; Neuville et al., 2010; Park & Min, 2010).

For Fe-oxide-containing silicate melts, a FeO/Fe_2O_3-aware viscosity formulation demonstrates that iron speciation must be represented in the modeled chemical state (Kim et al., 2021b). The related Fe-saturation formulation identifies a different chemically specified regime (Kim et al., 2021a). Temperature and oxygen potential may shift the Fe^{2+}/Fe^{3+} balance; accordingly, atmosphere and redox-state measurements should be reported before transferring coefficients between regimes. Other studies of Al_2O_3-rich slag composition and network structure (e.g., Qin et al., 2022; Ren et al., 2026) provide structural context, not direct evidence

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establishing an oxygen-potential-driven Fe redox effect in those systems. The cited bibliographic descriptions alone do not quantify its viscosity magnitude.

Polymerization is not a unique, measurable quantity across all melts. Reported structural units depend on the analytical method, spectral assignment, and composition; specify the applicable definition before comparing correlations. (Singh et al., 2021; Sohn & Min, 2012; Sukenaga et al., 2014; Sukenaga et al., 2011; Sun et al., 2018).

Apparent disagreements in the role of alumina may reflect changes in coordination, charge compensation, or the co-varying basic oxide fraction. Holding one oxide concentration fixed does not necessarily isolate one structural mechanism. (Sun et al., 2015; W. Wang et al., 2019; Y. Wang et al., 2026; Wang & Sohn, 2018; Wang et al., 2015).

The value of structure-based modeling lies in restrictions on chemically plausible behavior, not in guaranteed numerical superiority. The calibration domain and whether descriptors are measured or calculated remain essential. (Wang et al., 2014; Wang et al., 2024; Wen et al., 2023; Xing, Pang, Mo, et al., 2020; Xu et al., 2026).

Multicomponent extensions should establish how structural populations and the model coefficients respond when an additional oxide is introduced. A fit to a binary subsystem cannot itself validate that response. (Xuan & Zhang, 2023).

4. Experimental Determination and Data Reliability

Rotating-cylinder, bob, oscillating-crucible, and vibrating-probe methods measure viscosity using different mechanical assumptions. Geometry, end effects, temperature uniformity, calibration, and surface films can affect results, even for identical bulk compositions. Without the protocol and uncertainty budget, we cannot assess between-laboratory agreement.

A high-temperature record should report post-measurement composition, gas atmosphere and—if relevant—oxygen partial pressure, container material, heating–cooling

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path, residence time at each set point, and signs of precipitation or volatilization. Nominal feed chemistry may differ from the melt after crucible reactions or volatile losses, especially in sodium-, potassium-, and fluoride-bearing slags.

Experimental datasets intended for model calibration should distinguish directly measured values from digitized curves or fitted reconstructions. Repeated points from one original experiment must not appear as independent observations in a validation split. Before comparing errors across studies, standardize viscosity units, log transforms, temperature definitions, and whether measurements were obtained on cooling or heating.

Table 2 defines the experimental information required to decide whether viscosity measurements from different laboratories can support the same calibration or validation exercise.

Table 2. Measurement metadata required for a valid viscosity comparison.

Control	Minimum record	Risk if omitted
Chemistry	After-test oxide analysis	False nominal state
Thermal history	Ramp, dwell, heating/cooling	Hidden crystallization
Redox	Atmosphere and pO_2 when relevant	Unknown Fe/Ti speciation
Metrology	Geometry, calibration, uncertainty	Incommensurate datasets

Note. Qualitative assessment developed for this review; no pooled accuracy values are inferred from heterogeneous publications.

Agreement among laboratories cannot be established simply by a matching bulk oxide formula.

Measured viscosity is conditional on the instrument, imposed shear, crucible chemistry, temperature measurement, and residence time at temperature. These conditions should be documented alongside the composition of the recovered specimen. (Alam et al., 2021; Bai et al., 2020; Bale et al., 2016; Chebykin et al., 2017; Cheremisina et al., 2023).

Agreement between rotating-cylinder and alternative viscometry is not automatic near incipient crystallization. Apparatus geometry, transient solids, and heating history can alter the

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material response each method samples. (Han et al., 2016; Huang et al., 2020; Jung, 2010; Jung & Van Ende, 2020; Kondratiev & Jak, 2011).

Validation datasets need a consistent definition of the fully liquid interval. Results recorded during cooling should not be pooled with high-temperature steady-state measurements merely because nominal oxide percentages agree. (Laabs et al., 2022; Levchenko et al., 2025; Liu et al., 2019; Rimal & Tangstad, 2025; Z. Wang et al., 2019).

Experimental uncertainty must account for instrumental calibration, chemical drift, and phase-state uncertainty; a small instrumental error bar alone cannot establish a reliable benchmark. (Xu et al., 2015; Xuan et al., 2025).

5. Classical Empirical and Semi-Empirical Models

Arrhenius, Weymann–Frenkel-type, Urbain, Riboud, Iida, and Mills formulations range from convenient correlations to physically motivated approximations. Their compact parameters aid rapid furnace calculations, but simplicity does not ensure universal validity. Applicability depends on the chemistry and temperature range used for fitting.

Composition-only regressions may suit restricted families of fully liquid slags, particularly when oxidation state and phase content vary little. Their precision can mislead if fitted parameters absorb experimentally uncontrolled effects. Empirical equations remain useful engineering tools when paired with a calibration envelope, independent validation, and clear limits on extrapolation.

Figure 2 distinguishes six descriptive model families: empirical, semi-empirical, structural, CALPHAD-coupled, data-driven, and physics-informed/hybrid. Table 3 uses exactly these same six categories. A model can belong to more than one family (for example, a machine-learning regressor with thermodynamic descriptors); this taxonomy describes its information content and assumptions, not a hierarchy of accuracy.

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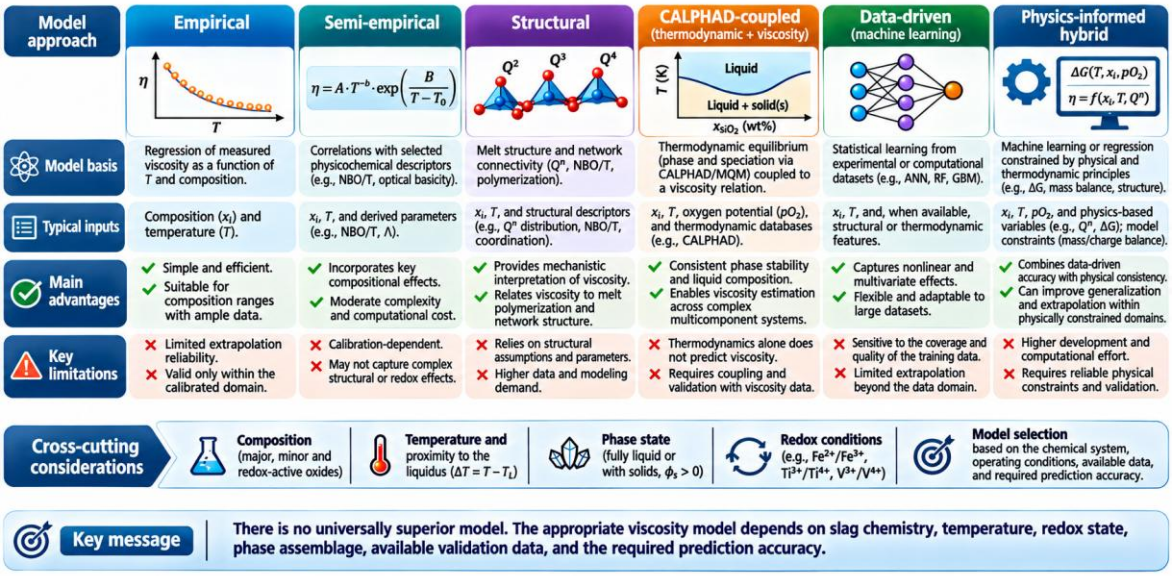

Figure 2. Comparison of empirical, semi-empirical, structural, CALPHAD-coupled, data-driven, and physics-informed approaches.
Note. Original conceptual illustration prepared for this review; scientific content is synthesized from the references discussed in the accompanying text.

No position in this classification establishes a model's accuracy. Only testing the selected formulation against observations representative of the operating domain can answer that question.

Table 3 compares model families by inputs, melt representation, extrapolation risk, and failure conditions. Errors across studies are not ranked because datasets, loss functions, and train–test partitions differ. Quantitative comparisons require applying each implementation to common experimental records.

Table 3. Qualitative comparison of principal viscosity modeling families.

Family	Primary input	Advantage	Critical restriction
Empirical	Oxide composition and T	Rapid calculation within fitted systems	Extrapolation outside calibration range
Semi-empirical	Composition, T, fitted physical terms	Compact but constrained functional form	Coefficients and validity domain system-specific
Structural	Composition, structural descriptors, T	Mechanistic interpretation	Uncertain or sparse independent structural measurements

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CALPHAD-coupled	Thermodynamic phase/species inputs, T	Thermodynamically consistent state screening	Additional calibrated transport law required
Data-driven / ML	Curated measurements and numerical descriptors	Flexible nonlinear interpolation	Leakage, domain shift, uncertainty calibration
Physics-informed / hybrid	Combined physical constraints and data	Can integrate phase and structural information	Component uncertainties; independent validation still required

Note. Qualitative assessment developed for this review; no pooled accuracy values are inferred from heterogeneous publications.

The comparison exposes a common trade-off: additional structural or thermodynamic inputs may improve interpretability, but they also introduce parameters and assumptions that require scrutiny.

Classical correlations are economical when their input chemistry and temperature remain within a documented fit domain. Do not interpret fitted coefficients as transferable structural parameters without independent physical evidence. (Gan et al., 2017; Guo et al., 2024; Hu et al., 2021; Mills et al., 2016; Mills et al., 2011).

Two correlations may produce similar residuals over the same well-characterized liquid window yet diverge when oxide concentrations leave that window. A comparison restricted to calibration residuals therefore cannot decide industrial suitability. (Mudersbach et al., 2011; Pereira, 2026d; Seok et al., 2010; Siafakas et al., 2018).

When a model represents basicity with a single ratio, different combinations of MgO, Al_2O_3, and Fe oxides may map to the same input despite distinct liquid structures. Such degeneracy is a structural limit of the descriptor rather than a numerical fitting problem. (Song et al., 2011; You et al., 2021; Zhang et al., 2021).

6. Structural Models

Structural approaches aim to connect viscous transport to local bonding, network connectivity, and the activation barrier for rearrangement. Their advantage is interpretability

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across related melts: changes in oxygen speciation or network units can be linked to the direction of a viscosity response. That interpretation, however, depends on the reliability of the structural state assigned to each composition.

Raman-informed models and descriptions based on the distribution of silicate or aluminate units provide an intermediate level of mechanistic detail between a global polynomial and an atomistic calculation. Structural data are unevenly available across industrially used multicomponent systems. Moreover, observed structural motifs do not automatically establish a unique flow mechanism; different local environments may produce similar bulk viscosity.

The structural approach is most convincing when it predicts rather than merely rationalizes an unseen experimental response. A sound validation protocol therefore withholds whole compositional families or redox conditions, not only random individual points. Failure under such a test is scientifically informative: it identifies structural variables missing from the chosen state description.

7. Thermodynamic and CALPHAD-Coupled Models

Thermodynamic software such as FactSage and Thermo-Calc is valuable because it can calculate phase equilibria, chemical potentials, and liquid composition consistently within the relevant database. In CALPHAD-based workflows, thermodynamic functions may supply structural or chemical descriptors used by a separate viscosity expression. Nevertheless, equilibrium thermodynamics alone does not determine a transport coefficient, and no thermodynamic coupling should be presented as a parameter-free prediction of viscosity. The link between thermodynamic input and an independently parameterized viscosity relation is also treated in Pereira (2026a).

Modified Quasichemical Model (MQM) formulations and ionic two-sublattice descriptions organize liquid solution behavior differently. Their viscosity extensions therefore depend on both the quality of the underlying thermodynamic assessment and the form and

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calibration of the transport-property relation. An internally consistent extrapolation from binary to higher-order systems remains a hypothesis to be tested experimentally, rather than an automatic consequence of a robust Gibbs-energy database.

The strongest use of thermodynamic coupling is the ability to evaluate whether the specified temperature and composition correspond to one liquid phase or to a heterogeneous assemblage. Where crystals are stable, the calculated liquid fraction can serve as input to a separate effective-viscosity model. This modular approach makes the scope of each submodel explicit, though calculated equilibrium phase fractions may differ from those realized during finite-rate cooling or reaction.

Thermodynamic databases constrain equilibria and can supply phase compositions or species fractions; viscosity remains a kinetic transport property that needs an additional constitutive description. Database consistency does not by itself establish viscosity accuracy. (Alves et al., 2021; Brosh et al., 2012; Jung, 2024; Kim et al., 2021a; Kim et al., 2021b).

Models informed by quasi-chemical or related liquid descriptions can exploit consistent chemical states across composition space. Their extrapolation nevertheless inherits uncertainty from both the equilibrium assessment and viscosity parameterization. (Kim et al., 2012; Kondratiev et al., 2012; Mao et al., 2011; Pereira et al., 2023; Rocha et al., 2018).

An oxide database may accurately predict liquidus relationships in a system yet have sparse viscosity measurements for that same composition family. Independent testing of both outputs is consequently required. (Suzuki & Jak, 2013; Tan et al., 2023; Tang et al., 2022; Wu et al., 2015; Xuan et al., 2022).

Comparison of CALPHAD-linked approaches should specify database version, liquid model, treatment of oxidation states, and the calibration dataset. Otherwise, a difference attributed to model family may instead arise from inconsistent thermodynamic inputs. (Z. Yan et al., 2019).

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8. Comparison of Predictive Performance

Comparing predicted and measured viscosity requires a transparent definition of the error metric and the benchmark domain. Suitable metrics include mean absolute error (MAE), root mean square error (RMSE), mean absolute percentage error (MAPE), and the logarithm of the ratio ηpred/ηexp. Because viscosity can span several orders of magnitude, log-ratio distributions are often easier to interpret than unqualified absolute errors; each metric nevertheless emphasizes a different part of the dataset.

A defensible benchmark separates at least four tasks: reproducing calibration points, interpolating within represented systems, predicting held-out chemical families, and predicting under different redox or phase conditions. Random train–test splitting of neighboring points from the same experimental series can considerably overstate transferability. Grouped validation by publication, experimental campaign, or compositional system is more demanding and more informative for industrial selection.

Figure 3 assesses model applicability against the presence of calibration evidence, redox and phase-state effects, and the need for independent validation. Its categories are interpretive rather than quantified reliability limits.

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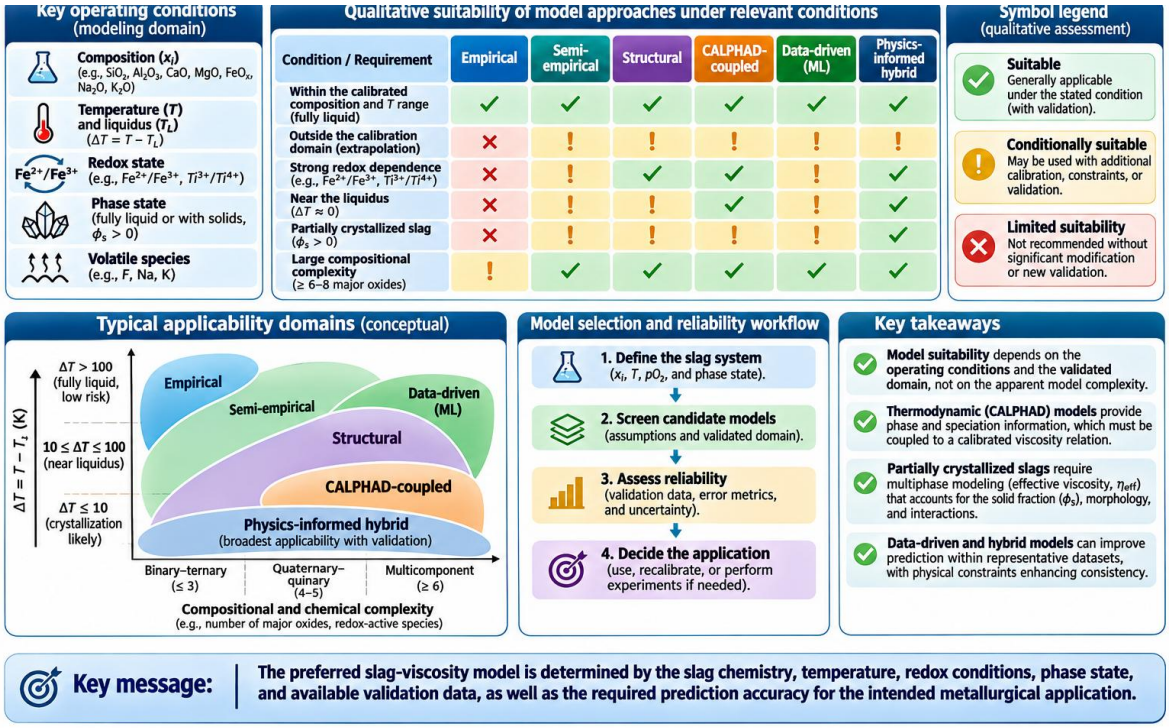

Figure 3. Qualitative model applicability, validation requirements, and uncertainty considerations.
Note. Original conceptual illustration prepared for this review; scientific content is synthesized from the references discussed in the accompanying text.

The suitability assessment must therefore be read as a screening aid. No symbol or model-family label replaces a measured, domain-specific error estimate.

Table 4 proposes a domain-based validation protocol rather than numerical performance values that the supplied references do not provide in a harmonized form. Figure 3 maps the transition from familiar liquid compositions to environments where phase behavior and oxidation state can dominate. Error estimates must be attached to these domains rather than presented as a single universal score.

Table 4. Hierarchical benchmark for predictive-performance claims.

Validation set	Split definition	Question answered
Calibration	Training records	Parameter fit only
Interpolation	Held-out points in known systems	Local prediction
Extrapolation	Held-out chemical systems	Transferability

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Phase/redox shift	Unseen pO_2 and phase conditions	State robustness

Note. Qualitative assessment developed for this review; no pooled accuracy values are inferred from heterogeneous publications.

A single headline RMSE collapses categories of uncertainty that have different industrial consequences.

9. Why Viscosity Models Fail

Composition extrapolation is the most familiar source of predictive failure, but structure mediates its consequences. A nominal change in CaO/SiO_2 ratio or Al_2O_3 content may cross a region in which charge compensation, network connectivity, or phase stability changes qualitatively. An extrapolation may therefore fail even when its composition vector is only a modest Euclidean distance from the training points.

Phase inconsistency is a more fundamental failure: a homogeneous-liquid model is asked to predict the rheology of a two-phase or three-phase material. If crystallization changes rapidly near the liquidus, the apparent temperature dependence can become much steeper than that of the residual liquid. This effect cannot be corrected by simply refitting an activation energy if the solid fraction and particle interactions remain unmeasured.

Redox variation creates a second hidden dimension in nominal oxide-based datasets. Fe^{2+}/Fe^{3+} and Ti^{3+}/Ti^{4+} partitioning depends on conditions not fully specified by bulk elemental chemistry. Similarly, volatilization of fluoride or alkali species, refractory dissolution, or contamination may make the post-test composition different from the formulation used in a prediction. Failure can then reflect incomplete input state definition rather than a deficient mathematical architecture.

Statistical failures arise when flexible regressions exploit correlated composition variables, favor densely measured systems, or fit lab-specific offsets. Strong test statistics can mislead when test data share campaigns, temperature series, or nearby compositions with

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training data. Credibility statements should separate model error, measurement uncertainty, dataset coverage, and process-state uncertainty.

Cr-bearing and Fe-bearing industrial slags illustrate how speciation and precipitation can change simultaneously. A discrepancy observed during cooling cannot be assigned uniquely to the redox treatment until the solid fraction has been assessed. (Chen et al., 2026; Jiao et al., 2017; Kim & Min, 2021; Lee & Min, 2018; Madej, 2025).

Volatile constituents and reactive crucible materials may shift the post-test chemistry away from the weighed mixture. The model should be evaluated at the measured liquid composition where possible. (Park & Min, 2011; Pereira, 2026e; Shen & Wu, 2021; Shen et al., 2019; Song et al., 2023).

Extrapolation across a primary phase boundary changes the object being predicted. In that regime, a failure of a liquid-viscosity equation is not necessarily evidence that its homogeneous-liquid calibration was defective. (Sukenaga et al., 2013; Tian et al., 2025; Q. Wang et al., 2026; Wang et al., 2020; Xiao et al., 2022).

Even in an apparently single-phase liquid, a simplified composition index can conceal oxide-specific interactions. The practical check is independent prediction along paths that change each component separately. (Yang et al., 2020; Yang et al., 2021; Yu et al., 2011).

10. Partially Crystallized Slags and Effective Viscosity

For a suspension, effective viscosity ηeff depends on the liquid viscosity ηliq, solid volume fraction φ, particle size and shape, aggregation, and imposed shear. The Einstein–Roscoe family is frequently used as an engineering approximation, ηeff = ηliq(1 − φ/φm)^(−n), with an empirical maximum packing fraction φm and exponent n. These parameters are not universal constants for crystal-bearing industrial slags, and φ must represent volume rather than mass fraction.

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Solid morphology can change despite a nearly constant total fraction. Needle-like, dendritic, or agglomerated crystals may affect flow more than compact particles, while entrained bubbles add another dispersed phase. Thus, an equilibrium solids fraction with a generic suspension multiplier is only an approximate engineering model until rheological tests establish its valid shear-rate and morphology range.

For high-Cr_2O_3, high-TiO_2, MgO-rich, and Al_2O_3-rich systems, crossing a primary phase boundary may matter more than a modest increase in liquid polymerization. Industrial measurements should report both thermal trajectory and phase-state evidence. Table 5's comparison of ηliq and ηeff shows how apparently inconsistent values can arise without either source being erroneous.

Table 5. Distinct physical domains of liquid and effective slag viscosity.

Feature	**Homogeneous liquid**	**Partially crystallized slag**
Property	ηliq	ηeff
State variables	T, composition, redox	T, liquid chemistry, φ, morphology, shear
Constitutive form	Newtonian often plausible	Potential non-Newtonian behavior
Failure check	Chemistry and liquid range	Phase fraction and suspension rheology

Note. Qualitative assessment developed for this review; no pooled accuracy values are inferred from heterogeneous publications.

A reported viscosity for a solid-bearing slag cannot be compared directly with a homogeneous-liquid prediction unless the phase state and rheological measurement conditions are reconciled.

Crystallization introduces an extra state variable, the solid volume fraction, that cannot be replaced by nominal bulk chemistry. Equilibrium calculations can estimate a limiting phase assemblage but cannot determine crystal morphology or aggregation on their own. (Chen et al., 2023; Deng et al., 2020; Gao et al., 2017; He et al., 2021; Ilyushechkin et al., 2020).

The Einstein–Roscoe-type relation is a conditional suspension approximation rather than a viscosity law for a homogeneous oxide liquid. Directly relevant experimental work on

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both slags and solid–liquid mixtures is identified in the bibliography (Xu et al., 2015); near-liquidus measurements and crystal characterization are necessary to establish whether an effective packing fraction or exponent can be transported to another particle population. The values of φm and n therefore require system- and shear-regime-specific calibration. Viscosity–structure papers on fully liquid slags (Kim & Sohn, 2012; Lin et al., 2025; J. Liu et al., 2024) and machine-learning viscosity studies (Jia et al., 2026) do not, on their titles alone, demonstrate universal suspension exponents and are not offered as direct support for that claim.

When the melt approaches the liquidus, heating and cooling paths may produce different rheological responses. Reporting thermal history is therefore essential before identifying a break temperature as a reproducible material constant. (Ma et al., 2021; Nigam et al., 2026; Pang et al., 2025; Park & Min, 2014; Park & Sohn, 2017).

The transition from liquid to effective viscosity matters particularly for slag-flow and gasification applications, where local temperature varies continuously, and crystallization can be spatially heterogeneous. (Saigo et al., 2022; Saito et al., 2020; Wang et al., 2017; Wang et al., 2021; Wang et al., 2016).

The casting context is illustrated by studies explicitly addressing mould-flux viscosity and composition (W. Yan et al., 2019) and a review of mold-flux development for high-Al steels (Wang, W., et al., 2016). Their subject matter supports the need to assess flux chemistry and casting conditions, but a viscosity result alone does not verify lubrication performance or heat flux: such coupled outcomes need dedicated measurements. The coal-gasification and reduction-related slag studies previously grouped here (Wu et al., 2026; Wu et al., 2016; Xin et al., 2022; Xu et al., 2024) concern other physical contexts and should be used only as analogies for chemistry- or phase-dependent viscosity, not as direct measurements of mold lubrication or casting heat transfer.

Particle loading is not the only source of non-Newtonian behavior; bubble content and shear history may also affect the measured response. A suitable process-scale model may need

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a multiphase formulation. (Yehorov et al., 2024; Yeo et al., 2020; Zhang et al., 2025; Zhang et al., 2026).

11. Machine Learning and Hybrid Models

Artificial neural networks, random forests, boosted models, Kriging, and other data-driven approaches can interpolate high-dimensional viscosity datasets without imposing a single analytical chemistry–structure relation. The price is sensitivity to the representativeness of the training space, to preprocessing decisions, and to database provenance. A method that accurately predicts neighboring compositions may be unreliable for a new oxide system or an unrepresented phase field.

Interpretability tools can rank input influence within a fitted dataset; they cannot by themselves establish causal structural mechanisms. Apparent feature importance for basicity, for example, may reflect correlation with Al_2O_3, flux additions, or the operating temperature distribution. Such diagnostic results should be compared with physically expected trends and, ideally, with controlled hold-out experiments.

Hybrid workflows that combine phase predictions, structural descriptors, and uncertainty-aware regressors are promising because they can constrain inputs and flag out-of-domain cases. Their central design decision is whether phase state and redox are treated explicitly rather than hidden in a chemical composition vector. The appropriate validation includes unseen chemical families, entire experimental publications, and temperatures near first crystallization.

Machine-learning predictions should be validated on entire withheld chemical systems or experimental campaigns, not only on randomly held-out rows from densely sampled temperature curves. (Cai et al., 2022; Chen et al., 2025; dos Anjos et al., 2024; Li et al., 2022; Lyu et al., 2022).

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SHAP and other feature-attribution methods describe dependence within the fitted dataset. They should not be presented as experimental evidence for a particular microscopic flow mechanism. (Singh et al., 2026).

12. Industrial Translation

Industrial use converts model error into a decision risk. In blast furnace hearth drainage, slag flow may interact with coke-bed permeability, metal–slag stratification, and multiphase transport. For mold fluxes, lubrication and heat-transfer behavior depend on melting and crystallization as well as viscosity. In gasification, the slag must flow over a cooled wall under a rapidly changing thermal profile. A universal viscosity threshold is therefore less useful than an application-specific operating window.

In electric-arc furnaces, secondary steelmaking, ferroalloy production, and copper smelting, equilibrium chemistry varies with oxidation practice and process stage. A predicted increase in viscosity may affect foaming, metal droplet entrainment, refractory contact, or tapping in different ways. Model choice should reflect the process mechanism of interest, not merely the availability of input oxides and temperature. Titanium-bearing slag engineering provides a related case where composition, phase assemblage, and operating targets must be considered together (Pereira, 2026b).

An operationally meaningful assessment asks whether the uncertainty range changes the selected temperature, flux addition, refractory protection strategy, tapping schedule, or slag-cleaning design. Where the margin is narrow, an inexpensive targeted viscosity measurement and a confirmatory phase analysis may provide more engineering value than choosing between two models whose reported aggregate errors differ slightly. Figure 4 gives a practical decision sequence to make that choice explicit.

Figure 4 depicts a proposed, unvalidated phase-aware screening sequence, not a proven industrial decision protocol. Stage 1 — define input state: record measured/post-test chemistry, T and operating range, oxygen potential or atmosphere, thermal path, and application-specific

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outputs; if these are missing, identify state-specification uncertainty and request targeted sampling. Stage 2 — screen phases: use a thermodynamic database with its version specified, complemented where possible by observed crystals and solid fraction; when the state is multiphase, select a separately calibrated effective-rheology relation instead of applying a homogeneous-liquid model. Stage 3 — establish candidate-model domain: compare oxide ranges, redox assumptions, liquid-only validity, data provenance, and independent validation; reject or mark unsupported extrapolations. Stage 4 — characterize uncertainty: distinguish measurement uncertainty, parameter or predictive uncertainty, model-form discrepancy, phase-equilibrium uncertainty, and unknown or mislabeled state; statistical confidence intervals alone cannot bound an uncharacterized phase or redox error. Stage 5 — propagate credible ranges into the actual drainage, tapping, inclusion-removal, or heat-transfer decision and compare against a tolerance defined by that application, never a universal viscosity threshold. Stage 6 — act: accept provisionally if the decision is robust over a supported range; otherwise measure the priority missing variable, recalibrate on independent relevant data, change model class, or suspend numerical certification where the error cannot be defensibly bounded. Highest priority is assigned to post-test chemistry and direct phase evidence whenever these can change the physical object of prediction; replicate viscometry or additional calibration follows once that state is characterized.

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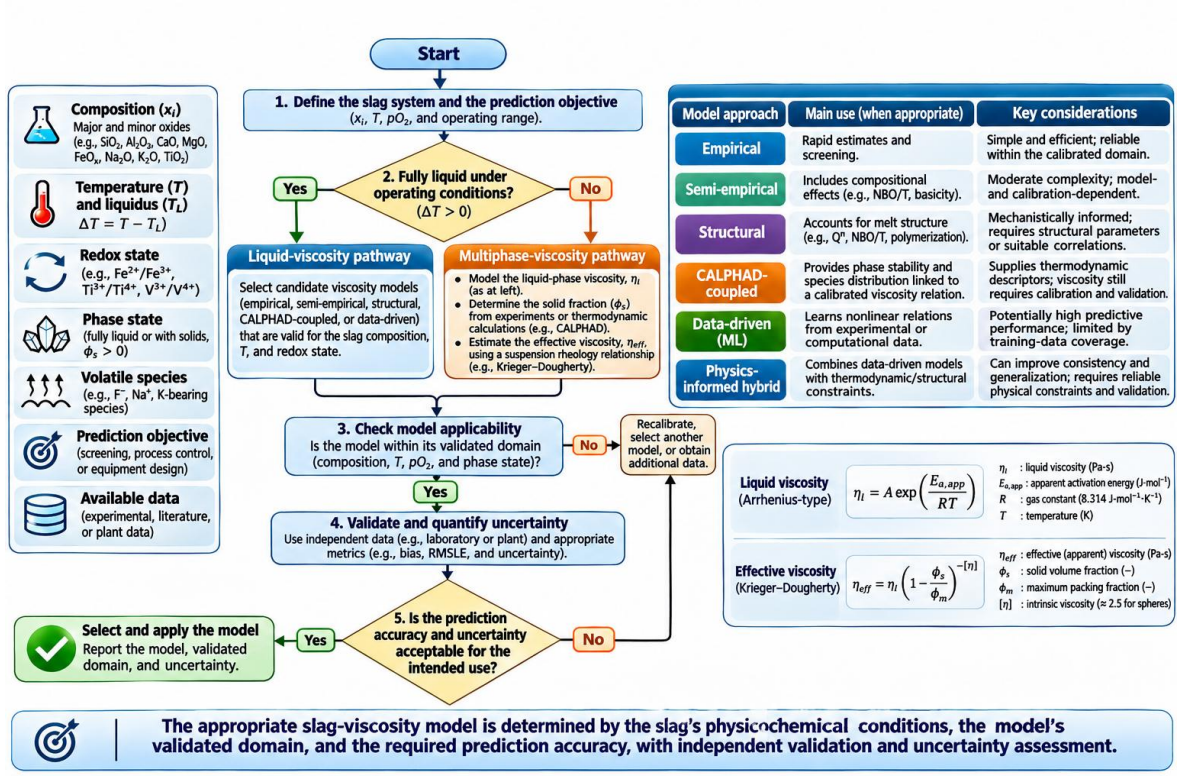

Figure 4. Phase-aware decision framework for selecting and validating industrial slag-viscosity models.
Note. Original conceptual illustration prepared for this review; scientific content is synthesized from the references discussed in the accompanying text.

A numerical uncertainty interval is meaningful only when measurement coverage, experimental state, calibration, and validation support its construction. If these prerequisites are absent, report the prediction as unbounded or unsupported rather than inventing a conservative numerical bound. Engineering tolerance is set by the specific control or design consequence; options include targeted experiments, independent validation, or a model incorporating solid–liquid rheology. This workflow remains a conceptual decision aid and has not been prospectively validated in an operating plant.

Blast-furnace, steelmaking, gasification, and non-ferrous slag applications have different objective functions. A pooled error statistic does not replace deciding whether the

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uncertainty affects tapping, drainage, or heat-transfer constraints. (Bartzsch et al., 2023; Chen et al., 2014; Kim et al., 2018; Kong et al., 2021; Lee et al., 2025).

Inclusion removal and metallic-droplet settling depend on viscosity, density difference, interfacial tension, geometry, and residence time. Model relevance should be tested within the coupled process equation. (Li & Ni, 2016; Luz et al., 2018; Naim et al., 2026; Pereira, 2026b). The interfacial context of droplet coalescence is reviewed separately by Pereira (2026c).

For the industrial selection problem, uncertainty should be propagated to the decision variable. If every plausible viscosity model yields the same control action, further model complexity has limited immediate value. (Svantesson et al., 2020; Tangstad et al., 2021; Yao et al., 2016).

13. Conclusions

A defensible prediction workflow begins with analyzed rather than merely nominal chemistry, a documented temperature range, and the relevant oxygen potential. It then establishes whether the material is fully liquid over that range. Only after this phase check should you select a viscosity model based on its chemical coverage, calibration data, independent validation, and ability to represent the intended operating conditions.

The most consequential gaps are shared reference datasets with documented oxygen potentials and thermal histories, measurements across the onset of crystallization, experimental reporting of solid morphology, and independent evaluations that exclude whole laboratory campaigns from model fitting. We also need better information on uncertainty propagation from composition measurement to phase fraction and, finally, to process decisions.

No empirical, structural, thermodynamically coupled, or machine-learning viscosity model can be declared universally superior based on incomparable published error statistics. The reliable prediction domain depends on how well the model's material state matches the actual chemical, thermal, redox, and phase conditions. For industrial slags, explicit screening for precipitation and independent validation are prerequisites to a credible model ranking.

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When these conditions cannot be demonstrated, the proper engineering response is bounded prediction accompanied by targeted measurement.

Declarations

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Conflict of Interest

The author declares no conflict of interest.

Data Availability

No new experimental datasets were generated. All quantitative values discussed in the review are traceable to the cited literature.

Author Contributions

The author performed conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation.

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