

Bottom Ash Bridging in Pulverized-Coal Boilers: Mechanisms, Diagnosis and Prevention

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Abstract: Bottom ash bridging is the formation of a self-supporting arch, crust or consolidated clinker mass across the furnace bottom or hopper flow path. The event is rarely caused by a single factor. It normally develops through the interaction of ash chemistry, localized temperature variations in the furnace, combustion atmosphere, deposit residence time, hopper geometry, quenching performance and the extent of ash-removal. High furnace temperature, inadequate cooling, delayed discharge, hopper geometry & conditions, coal-quality variation and air & water leakage as primary contributors. This paper outlines the critical observations into a mechanism-based framework suitable for operating guidance, root-cause analysis, and monitoring. Particular emphasis is placed on the difference between ash softening, sintering, and complete melting; the role of iron, calcium and alkali fluxes; localized reducing conditions; and the fact that agglomeration can begin below the standard initial-deformation temperature measured by ash-fusion test. A robust prevention strategy should combine fuel & ash characterization, furnace heat-flux and combustion control, continuous ash extraction, uniform hopper cooling and water sealing, condition monitoring of grinders, gates, conveyors and hydraulic systems, and disciplined post-event deposit analysis. Plant-specific operating limits must be based on the boiler OEM design, actual coal blend, and historical operating data rather than the generic temperature limits alone.

Keywords: bottom ash, bridging, ash fusion temperature, combustion control, sintering, pulverized-coal boiler

1. Introduction

Bottom ash is the fraction of non-combustible mineral matter that leaves the radiant furnace as coarse particles, agglomerates or molten/semi-molten slag and is collected at the furnace bottom. Depending on boiler design, the material may be quenched in a water-filled hopper, discharged to a submerged scraper conveyor, crushed by clinker grinders and transported hydraulically or mechanically [1].

The purpose of this paper is to provide a detailed explanation of bottom ash bridging and a practical method for the investigation and prevention. It applies primarily to pulverized-coal boilers with wet & dry bottom-ash hoppers and/or submerged ash extraction systems. The basic terminologies are mentioned in Table 1.

Though this paper does not replace OEM operating

procedures, statutory requirements or site emergency instructions but emphasizes on the root-cause analysis, risk ranking framework, and laboratory scale investigations.

1.1 Objectives

- Define bridging and distinguish it from normal clinker formation.
- Explain thermal, chemical, mechanical and hydraulic mechanisms.
- Identify measurable precursors and diagnostic evidence.
- Provide preventive maintenance and laboratory recommendations.
- Present a repeatable root-cause and risk-ranking framework.

2. Terminology and Boiler Context

Table 1: Terminology used in bottom ash bridging [1]-[5]

Term	Technical meaning
Bottom ash	Coarse ash, slag fragments and agglomerates collected at the furnace bottom.
Clinker	A hard, sintered or fused ash mass formed by bonding of mineral particles.
Bridging	A self-supporting ash arch or crust that spans a flow opening and restricts discharge.
Sintering	Incipient / partial fusion of particles forming agglomerates through bonding.
Slagging	Deposition of molten or partially molten ash in high-temperature radiant zones.
Fouling	Deposit formation in lower-temperature convective sections, often involving alkali condensation and particle capture.
Ash Fusion Temperature (AFT)	Characteristic ash fusion temperatures observed in a standardized cone test: deformation, softening, hemispherical and fluid stages.
Eutectic phase	Specific mixture of two or more components that changes phase at a single, constant temperature that is lower than the melting point of any of the individual components
Reducing atmosphere	Oxygen-deficient environment where iron ore or mineral transformations may differ from those in oxidizing gas.

XRF	X-ray fluorescence (XRF) - a non-destructive analytical technique used to determine the elemental composition of materials.
XRD	X-ray Diffraction (XRD) - a non-destructive analytical technique used to determine the atomic and molecular structure of crystalline materials.
SEM-EDS	SEM/EDS (Scanning Electron Microscopy paired with Energy-Dispersive X-ray Spectroscopy) - an analytical technique that combines high-resolution surface imaging with precise elemental composition analysis.

A bridge may form directly across a hopper throat, above a grinder inlet, between furnace slopes, around water-wall protrusions, or within a constrained discharge chute. The exact profile of the bridging may differ from what it is shown in the

figure 1 and the size and locations may be unpredictable [6].

3. Mechanism of Bridge Formation

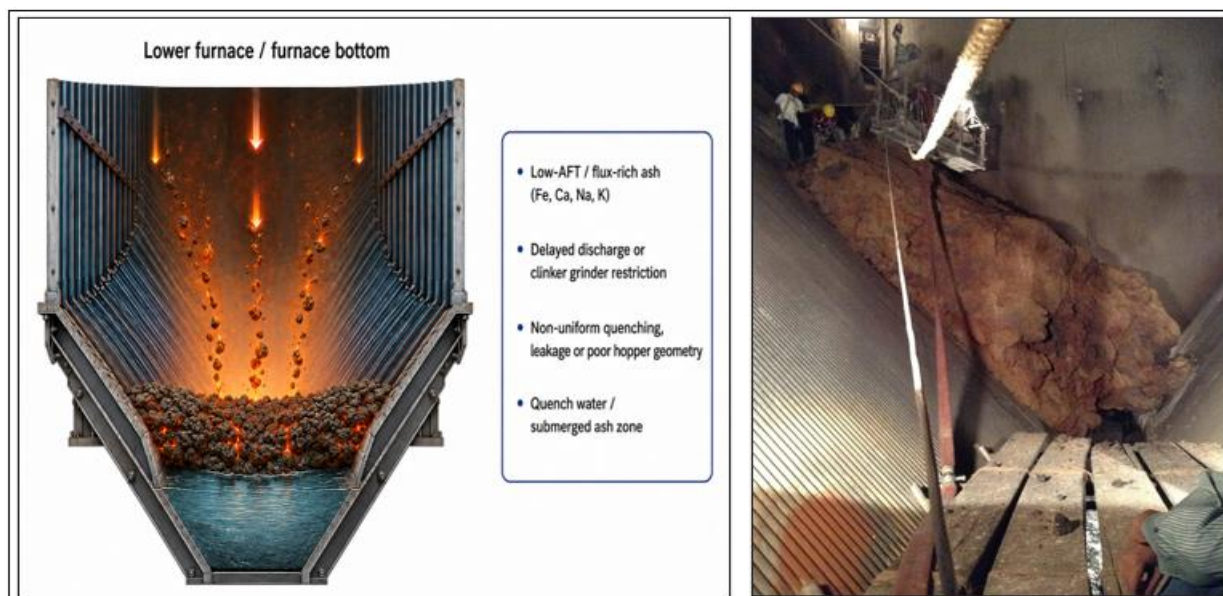


Figure 1: Coupled mechanism of bottom ash bridging [4], [5]-[8]

- 1) Ash particles enter into a high temperature regime wherein it softens and becomes sticky.
- 2) Particles collide with each other or with existing deposits and adhere. Fine particles fill the voids created by coarser ones.
- 3) Repeated stacked deposition, compaction and partial melting increase the deposit's strength. Low-melting phases and unburnt carbon particles act as binders.
- 4) If ash extraction is slow, residence time increases and the deposit grows laterally across the opening.
- 5) Cooling or quenching may strengthen the mass by rapid vitrification or thermal consolidation, while uneven cooling can create a rigid shell around a hotter core.
- 6) Once a self-supporting arch forms, incoming ash loads the bridge from above. The resulting mass may collapse suddenly, remain stable, or redirect heat to hopper walls.

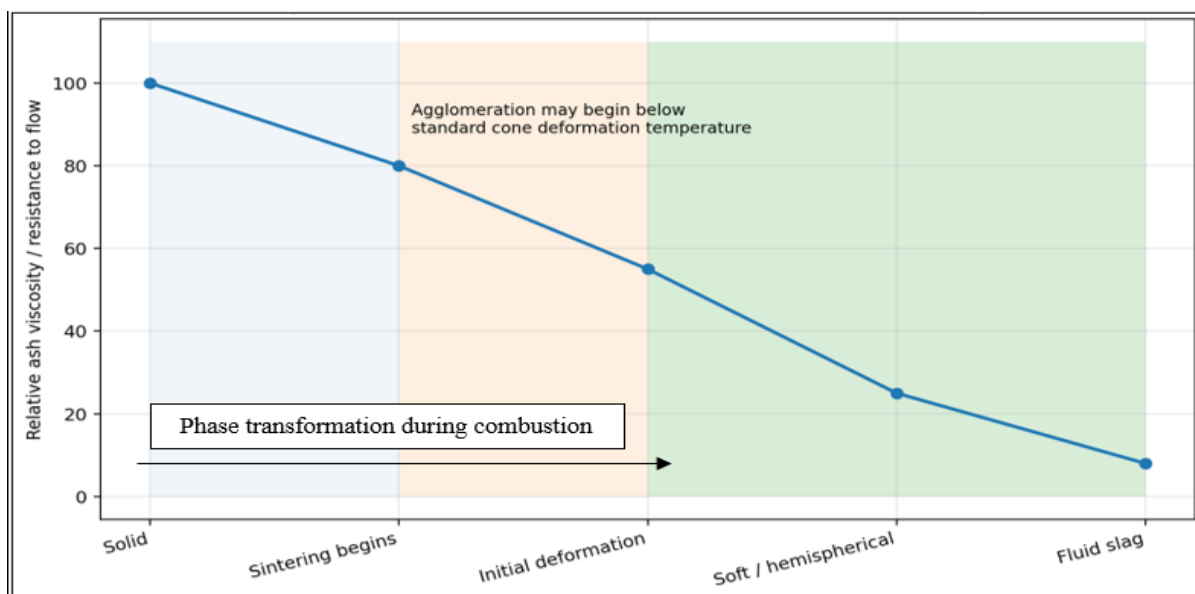


Figure 2. Relationship between temperature, ash viscosity and bridging risk [2], [3], [6]-[9]

Standard ash-fusion temperatures should not be interpreted as exact boiler transition temperatures (Figure 2). Real deposits can begin to sinter or agglomerate below the observed deformation temperature because individual minerals segregate, particles experience different

4. Contributing Factors

Atmospheres, and liquid eutectic phases can form locally [2], [3], [6]-[9].

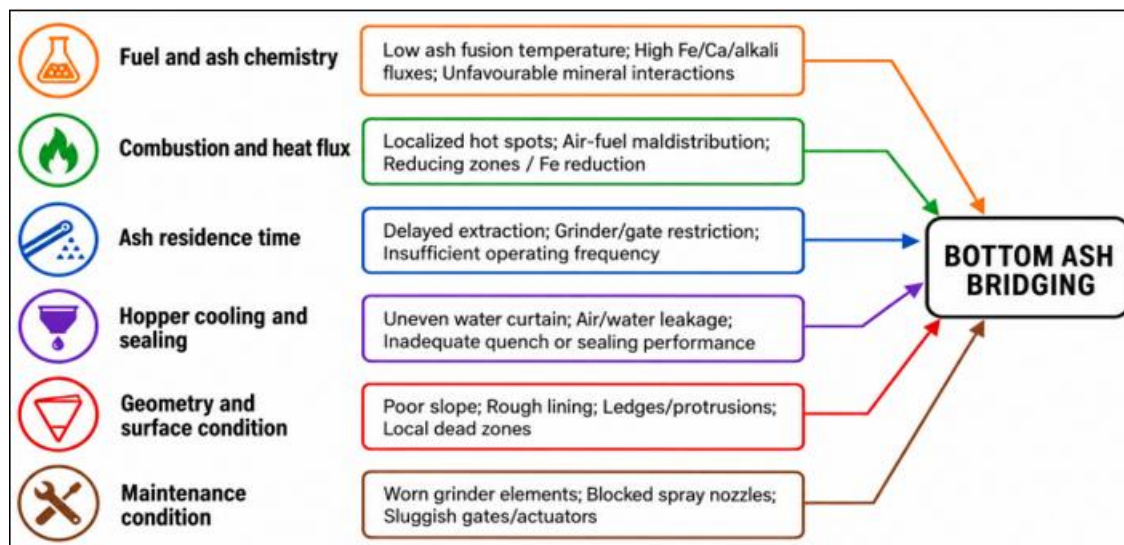


Figure 3: Main factors causing bottom ash bridging (Source: Author's illustration)

Table 2: Contributing factors and typical evidence [4]-[7]

Contributing Factors	Mechanism	Typical evidence
Fuel and ash chemistry	Low-melting minerals or eutectics create sticky surfaces and liquid binders.	Low AFT; elevated Fe_2O_3 , CaO , Na_2O or K_2O ; repeated issue after coal/blend change.
Combustion and heat flux	Localized hot spots increase particle softening; reducing pockets can change chemical compositions.	High CO , uneven O_2 , burner imbalance, flame impingement, mill/burner pattern dependence.
Ash residence time	Delayed extraction allows growth, sintering and load accumulation.	Low ash discharge, gate malfunction, grinder overload, conveyor restriction, Inefficient hydraulic evacuation system.
Hopper cooling and sealing	Uneven quenching or loss of water curtain creates abnormal thermal gradients and hard masses.	Water-level or pressure variation, blocked nozzles, high hopper skin temperature, steam generation.
Geometry and surface condition	Low slope, protrusions, damaged refractory or rough surfaces provide anchoring points.	Recurring bridge at same location; refractory damage; historical modification.
Maintenance condition	Wear, actuator problems and sensor unreliability reduce bottom-ash extraction capacity.	High grinder current, worn teeth, sluggish gate, false feedback, leaking hydraulic system. Faulty hydra ejector system, worn out ejector orifices.

4.1 Combustion-Related Triggers

The various conditions/ parameters leading to clinkering and subsequent bottom ash bridging are summarized in figure 3 and table 2. The details are as follows:

- Operation with an unfavorable mill combination or burner elevation that concentrates heat near the hopper.
- Poor secondary-air distribution, burner imbalance, excessive burner tilt or flame impingement.
- Intense local heat release during rapid load increase or unstable coal feed.
- High carbon monoxide and reducing zones caused by insufficient mixing, poor fineness, and low excess air [4], [7].
- Large unburnt char or pyrite-rich particles falling into the hopper and continue to burn.

minerals. The same Fe_2O_3 or CaO content can behave differently depending on whether it occurs in discrete minerals, clay-bound forms, carbonates, sulphates or glass-forming agents (Table 3) [5], [6], [7].

5.1 Ash-Handling and Cooling Triggers

- Intermittent or failed clinker grinder operation.
- Partially closed gate, actuator failure, foreign-object obstruction or high downstream backpressure.
- Low submerged scraper conveyor capacity, chain/flighting problem or excessive bed depth.
- Loss of water seal, insufficient make-up water, blocked quench sprays or abnormal water temperature.
- Sudden dislodging of a large furnace-wall clinker exceeding grinder or conveyor capacity.

5. Ash Chemistry and Mineral Transformations

Bulk oxide analysis is a practical first screening tool, but oxide percentages do not show how elements are distributed among

Table 3: Influence of ash components and phase families [5], [6], [7]

Component / phase family	General influence	Important qualification
SiO ₂ -Al ₂ O ₃ framework	Often raises refractoriness when present as high-melting aluminosilicates.	Can still form low-melting eutectics when combined with Fe, Ca or alkalis.
Iron-bearing minerals	Iron can act as a strong flux and promote low-viscosity melts	Reducing conditions may favor Fe ²⁺ bearing phases with lower melting behavior.
Calcium and magnesium	Can lower AFT in silica-alumina systems by forming calcium/magnesium aluminosilicates.	At some compositions, refractory Ca-rich phases may form; effect is non-linear.
Sodium and potassium	Strong fluxes; promote glass formation and sticky surfaces.	Even modest concentrations can be important when deposited on particle surfaces.
Sulfur-bearing phases	May participate in sulphates or low-temperature condensed deposits.	Influence depends strongly on atmosphere and interaction with alkalis.
Quartz, mullite, corundum	Generally high-melting or refractory phases.	Their protective effect depends on abundance, grain size and reaction with fluxes.

5.2 Why Reducing Conditions Matter

In oxygen-deficient zones, ferrous-bearing silicates and associated eutectics may melt at lower temperatures than corresponding oxidized phases. Therefore, ash-fusion testing in both oxidizing and mildly reducing atmospheres is valuable when a boiler exhibits high CO, poor mixing or low-O₂ operation [2], [3], [7].

5.3 Limits of Conventional Slagging Indices

Base-to-acid ratio, silica ratio, iron/calcium indices and similar empirical indicators can rank broad tendencies, but they should not be used as standalone pass/fail criteria. They do not capture mineral association, particle size effects, local atmosphere, boiler geometry, deposition rate or dynamic blend interactions [10].

6. Operational symptoms and consequences

Table 4: Operational symptoms, interpretations and immediate verification

Observed symptom	Possible interpretation	Immediate verification
Reduced or intermittent bottom ash discharge	Restriction, bridge or grinder feed limitation.	Confirm gate position, grinder current, downstream transport and physical flow.
Rising hopper skin / metal temperature	Ash accumulation, failed water curtain or loss of quench.	Validate sensor; inspect water flow, level, sprays and thermal pattern.
High or oscillating grinder current	Oversized clinker, excessive feed or mechanical damage.	Compare with ash flow; check vibration, sound and differential loading.
Furnace pressure disturbance	Sudden slag dislodging, steam release or altered gas flow.	Correlate event time with hopper and ash-handling trends.
High CO / Uneven O ₂	Combustion maldistribution or local reducing condition.	Review burner/mill pattern, air distribution and analyzer health.
Abnormal slag fall or loud impact	Large wall deposit detachment.	Inspect hopper load response and grinder/conveyor capacity.

6.1 Potential Consequences

The ill-effects of bottom ash bridging directly result in tangible and intangible losses. Potential consequences that may result from bottom ash bridging include the following:

- Loss of ash-removal capacity,
- Increase in furnace-bottom inventory.
- Overheating, distortion, cracking or refractory damage in the hopper.
- Sudden release of hot ash, steam and pressure when a bridge collapses.
- Damage to clinker grinders, gates, SSC chains, flights or slurry systems.

- Forced load reduction or unit shutdown.
- Reduced heat absorption,
- Increased furnace exit gas temperature and lower boiler reliability.
- Severe personnel risk during manual poking, lancing or inspection.

7. Diagnostic and Root-Cause Methodology

The diagnostic methodology can be summarized as given in table 4:

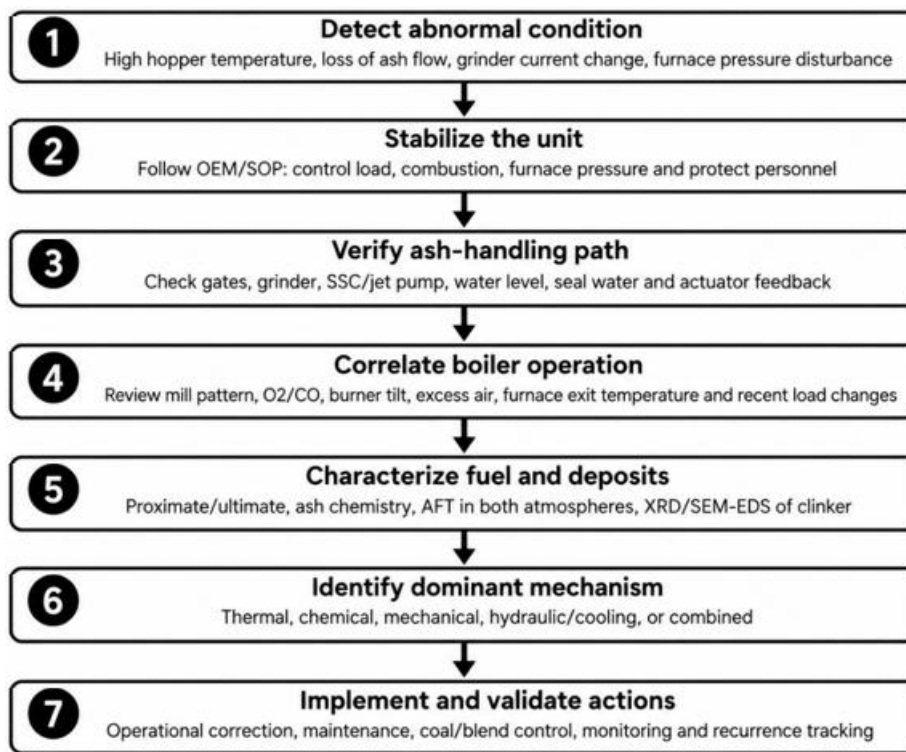


Figure 4: Recommended diagnostic workflow

8. Monitoring and Instrumentation

important for early detection of clinkering and bottom ash bridging.

Regular and prompt monitoring of the boiler by use of proper instrumentation (see. Table 5) and physical readings is

Table 5: Recommended monitoring and instrumentation

Monitoring item	Purpose	Good practice
Multiple hopper skin thermocouples	Detect localized accumulation or loss of cooling.	Use several elevations/sides; alarm on rate-of-rise and spatial imbalance, not only absolute temperature.
Grinder motor current and vibration	Identify overload, jam, wear or no-load operation.	Trend by operating state; distinguish mechanical fault from high ash feed.
Gate command and positive position feedback	Confirm actual opening.	Use independent limit/position feedback and stroke-time monitoring.
SSC/drag conveyor current or torque	Detect bed build-up or mechanical restriction.	Correlate with speed, water level and ash inventory.
Quench and seal-water flow/pressure	Verify uniform cooling and sealing.	Provide low-flow alarms and periodic nozzle proving.
Ash discharge quantity	Confirm mass removal.	Use weigh/volume estimates where practical; reconcile with coal ash input.
CO and O ₂ distribution	Identify reducing zones and mixing issues.	Use validated analyzers and compare left/right or furnace quadrants where available.
CCTV / thermal imaging at safe locations	Support visual confirmation.	Use only suitably protected equipment and OEM-approved viewing arrangements.

9. Prevention and Mitigation

9.1 Fuel and Blend Management

- Track coal chemistry and AFT for each major coal source and operational blend [2], [3], [11].
- Evaluate AFT in both oxidizing and reducing atmospheres when iron-rich ash or reducing operation is suspected. Under reducing condition, iron changes its chemical state and melting behaviour [2], [3], [7].
- Avoid blend transitions that produce low-melting eutectics even when individual coals appear acceptable. Presence of ferrous iron (Fe²⁺) acts as a powerful fluxing agent which readily reacts with silica in the ash and forms low melting

eutectic compound called fayalite (Fe₂SiO₄), which substantially lowers down the softening and melting temperature of the ash [6], [7].

- Use deposit history to establish the bands / limits for Fe, Ca, alkalis and AFT for trouble free operation.
- Maintain pulverizer fineness and reject removal to reduce large mineral/pyrite particles entering the furnace bottom.

9.2 Combustion Control

- Maintain balanced coal and air distribution among burners.
- Avoid persistent high CO, flame impingement and hot spots in the bottom part of the furnace.
- Review burner tilt, mill pattern and excess-air strategy after fuel changes.

- Control load ramps and stabilize combustion before the faster heat-input changes.
- Use furnace diagnostics tools such as O₂/CO mapping, acoustic/optical monitoring or CFD to identify recurrent hot regions [4], [10].

9.3 Ash Extraction and Hopper Management

- Operate ash evacuation continuously or at a frequency that prevents residence-time build-up.
- Keep both duty and standby ash-removal paths available where the design provides redundancy.
- Verify water level, quench flow, seal integrity and spray distribution in every shift.
- Maintain grinder clearances, teeth, bearing lubrication and protection logic.
- Remove geometric anchoring points during outages and repair damaged refractory/lining.
- After a large slag fall, confirm that downstream equipment can accept the transient load before normal firing is resumed.

9.4 Design Improvements for Recurrent Cases

- Incorporate instrumentation systems at known hot or blockage locations.
- Improve hopper slope, throat dimensions or internal surface smoothness subject to design & engineering review.
- Upgrade grinder capacity, gate actuation, SSC torque capability or redundancy where capacity is the limiting factor.
- Improve quench-water distribution and add nozzle blockage detection system.
- Use CFD coupled with ash-deposition predictive/control model to evaluate thermal and flow conditions before structural modifications [4], [10].

9.5 Use of combustion catalyst and clinker removal chemical

- Optimized usage of combustion catalyst to prevent formation of hard clinkers in the boiler.
- Localized usage of bottom ash bridging removal chemicals in case of bottom ash bridging event.

10. Emergency and Recovery Considerations

Safety-critical note: Manual poking, water lancing or opening access doors near hot ash bridge can expose personnel to sudden collapse, steam eruption, hot ash discharge and furnace pressure. Only approved site procedures and OEM guidance should be followed.

- Recognize and declare the abnormal condition early.
- Stabilize furnace pressure, combustion and load in accordance with the unit operating procedure.
- Protect hopper cooling and ash-removal equipment from thermal and mechanical overload.
- Establish exclusion zones around access doors, hopper and ash-discharge equipment.
- Do not introduce water onto hot ash unless the system is specifically designed and the method is approved.
- After recovery, inspect for deformation, refractory damage, grinder damage and hidden residual deposits before returning to normal operation.

11. Risk Ranking and Action Matrix

The risk ranking and action matrix for ash bridging for Bottom Ash Hopper is shown in Table 6.

Table 6: Risk ranking and action matrix

Risk level	Indicative condition	Recommended action
Low	Stable ash flow; normal temperature pattern; no grinder overload; coal/AFT within established envelope.	Continue routine monitoring and preventive maintenance.
Moderate	Increasing grinder load, intermittent ash flow, localized temperature rise, recent unfavourable coal/blend change.	Increase monitoring frequency; verify water/gates/grinder; monitor combustion and evacuation frequency.
High	Persistent flow reduction, rapid temperature rise, repeated overload of Clinker Grinder, high CO/hot-spot evidence in furnace.	Implement site abnormal operating procedure; reduce risk exposure and prepare controlled load intervention.
Critical	No ash flow with confirmed accumulation, rapid thermal excursion, structural distress, sudden pressure/steam events.	Follow emergency/OEM procedure, establish exclusion zone and initiate safe shutdown of Unit.

12. Conclusions

- Bottom ash bridging is the result of coupled thermal-chemical-mechanical failures due to the deposits adhesion, growth and strengthening across a constrained flow path.
- Though the ash fusion temperature is a useful screening indicator, but it does not fully reproduce particle heating rate, mineral segregation, local gas chemistry, residence time or surface interactions in a boiler [6]-[10].
- In addition to the high furnace temperature, local atmosphere, associated mineral, residence time, quenching and mechanical evacuation are equally important.
- Data capturing and operating evidence should be synchronized with the event specific operating sequence.

- Prevention depends on coordinated control of fuel quality, fuel combustion, ash extraction, hopper cooling, BAH equipment condition monitoring and pre-alert signaling.
- Optimized use of combustion catalyst and need based localized application of bottom ash bridging removal chemicals are being done.
- Characterization of ash using XRF, XRD, SEM-EDS, etc. is essential to understand its impact when repeated bridging occurs despite apparently acceptable coal quality. The results obtained from these tests provide in depth data regarding the elements present in the clinker samples, the transition phases that are formed and the physical composition of the clinker samples [5], [7], [9].

- Advanced mineralogical analysis of coal and ash coupled with CFD of furnace can help mitigate the recurrence of bridging events [4], [10].

References

- [1] Wisconsin Recycled Materials Resource Center, "Coal Bottom Ash/Boiler Slag - Material Description," University of Wisconsin-Madison. Available: <https://rmrc.wisc.edu/ug-mat-coal-bottom-ash-boiler-slag/> (accessed Sep. 9, 2026).
- [2] ASTM International, ASTM D1857/D1857M-24, Standard Test Method for Fusibility of Coal and Coke Ash. West Conshohocken, PA, USA: ASTM International, 2024. doi: 10.1520/D1857_D1857M-24.
- [3] International Organization for Standardization, ISO 540:2025, Hard coal - Determination of ash fusibility, 5th ed. Geneva, Switzerland: ISO, 2025.
- [4] H. B. Vuthaluru, N. Kotadiya, R. Vuthaluru, and D. French, "CFD based identification of clinker formation regions in large scale utility boiler," *Applied Thermal Engineering*, vol. 31, no. 8, pp. 1368-1380, 2011. doi: 10.1016/j.applthermaleng.2010.12.032.
- [5] B. Kamara, D. V. V. Kallon, and P. M. Mashinini, "Fouling and Slagging Investigation on Ash Derived from Sasol Coal Using ICP and XRF Analytical Techniques," *Applied Sciences*, vol. 12, no. 22, art. 11560, 2022. doi: 10.3390/app122211560.
- [6] F. E. Huggins, D. A. Kosmack, and G. P. Huffman, "Correlation between ash-fusion temperatures and ternary equilibrium phase diagrams," *Fuel*, vol. 60, no. 7, pp. 577-584, 1981. doi: 10.1016/0016-2361(81)90157-5.
- [7] G. P. Huffman, F. E. Huggins, and G. R. Dunmyre, "Investigation of the high-temperature behaviour of coal ash in reducing and oxidizing atmospheres," *Fuel*, vol. 60, no. 7, pp. 585-597, 1981. doi: 10.1016/0016-2361(81)90158-7.
- [8] J. J. Stallmann and R. C. Neavel, "Technique to measure the temperature of agglomeration of coal ash," *Fuel*, vol. 59, no. 8, pp. 584-586, 1980. doi: 10.1016/0016-2361(80)90236-7.
- [9] T. F. Wall, S. K. Gupta, R. P. Gupta, R. H. Sanders, R. A. Creelman, and G. W. Bryant, "False deformation temperatures for ash fusibility associated with the conditions for ash preparation," *Fuel*, vol. 78, no. 9, pp. 1057-1063, 1999. doi: 10.1016/S0016-2361(99)00017-4.
- [10] M. U. Degereji, D. B. Ingham, L. Ma, M. Pourkashanian, and A. Williams, "Numerical assessment of coals/blends slagging potential in pulverized coal boilers," *Fuel*, vol. 102, pp. 345-353, 2012. doi: 10.1016/j.fuel.2012.07.028.
- [11] M. Onifade, A. I. Lawal, S. O. Bada, and A. P. Shivute, "Effects of Proximate Analysis on Coal Ash Fusion Temperatures: An Application of Artificial Neural Network," *ACS Omega*, vol. 8, no. 42, pp. 39080-39095, 2023. doi: 10.1021/acsomega.3c04113.

Author Profile



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