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Specific aspects of vertical roller mills design selection

Abstract. The article analyzes specific design selection aspects of vertical roller mills, essential for grinding materials like granulated slag in the cement and mining industries. The research focuses on improving mill's working elements to enhance efficiency, reduce energy consumption, and increase wear resistance under harsh operating conditions. Modern innovative designs, including multi-roller and modular concepts with active redundancy, are reviewed for improved reliability. The comminution principle relies on energy-efficient compression and shear within the material bed. A comparative analysis of various mills configurations, differing in roller and table geometry, is presented, demonstrating how design adaptations such as specialized rollers for high-moisture slag optimize performance, wear rate, and energy efficiency.

Keywords: vertical roller mills, granulated slag, structural elements, mill capacity.

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Introduction.

Vertical roller mills (vrms) are instrumental tools underpinning modern technological processes in the cement, mining, and energy industries. They are widely employed for the grinding of various materials, with granulated slag occupying a particularly important place. In cement production, these mills have become a standard because slag cements, owing to their high strength characteristics and resistance to aggressive environments, are indispensable components of modern building materials.

The current stage of development in the construction industry is characterized by increasing demands for the efficiency of technological processes, especially in the production of cement and the processing of granulated blast furnace slags. One of the key areas of scientific research is the improvement of mill designs that ensure high technical and economic performance, particularly high specific throughput at reduced energy consumption. The rational use of energy during fine grinding is critically important for reducing the prime cost of construction materials and lowering the overall carbon footprint of the industry. The increase in the capacity of grinding installations and the complication of their operating conditions necessitate new approaches to the design of working elements such as rollers, grinding tables, and separation devices. Specifically, research is focused on optimizing the geometric parameters of these elements, improving drive systems, and implementing intelligent automation tools for the grinding process.

At the same time, the working elements of the mills operate under complex conditions characterized by intense abrasive and impact wear. This imposes stringent requirements on their wear resistance and reliability. One of the priority tasks of modern mechanical engineering is the application of high-performance construction materials, including alloy steels, wear-resistant alloys, and innovative protective coatings. A separate scientific and practical challenge is posed by vibrations that occur during mill operation and can lead to a reduction in equipment longevity and degradation of technological process stability. In this regard, the development of structural solutions aimed at minimizing dynamic loads and enhancing the reliability of the units is highly relevant.

Review of the research sources and publications. Vertical roller mills are recognized as some of the most efficient grinding devices currently available and can be used for the simultaneous grinding and drying of materials such as limestone, quicklime, cement raw material, talc, bauxite, magnesite, phosphate, feldspar, barite, graphite, and coal. The dominant uses for vertical roller mills are in cement raw meal production and coal grinding, but there are also numerous examples of the vertical mills' use in the mining industry.

In [1] lucas r.d. jensen, henrik friis, etc analyzes the influence of abrasive mineral concentration, specifically quartz, on the wear rates of vertical roller mill components operating in a closed-circuit comminution process. Structurally, the vrm uses hydraulic pressure to press rollers onto a rotating table, where material is ground, and a dam ring on the periphery controls the parabolic grinding bed. Due to simultaneous separation by a hot air flow, a key technical issue emerges in the process: minerals with lower grindability, such as quartz, up-concentrate in the grinding bed and in the stream returned from the separator. The study of synthetic mixtures of limestone and quartz sand confirmed that the quartz concentration in the grinding bed is the determining factor for the wear rate.

Publication [2] is dedicated to the empirical evaluation of the Thermal Efficiency of a vertical roller mill, model LM 53.3+3 with six rollers (3 Master + 3 Support), operating at the PT Semen Baturaja Tbk plant. The vertical roller mill is a key unit for simultaneous grinding and drying of clinker with additives (limestone, gypsum, pozzolan, fly ash), utilizing hot air from the great cooler as a heat transfer medium, along with heat generated by the clinker and the grinding rollers. The grinding process occurs on a rotating table, where the material layer is controlled by a dam ring, and subsequent separation of fine and coarse fractions (reject) is performed by a classifier. The methodology for estimating was based on the sequential calculation of the Mass Balance and Heat Balance. Based on three days of calculations, the average thermal efficiency of the vertical roller mill is in the range of 81–82%. The main conclusions are that the actual efficiency is satisfactory and economically advantageous, as it does not significantly deviate from the target design specification of 85%. A key factor reducing Thermal Efficiency is false air (cold air infiltration) due to damage to the mill casing, necessitating corrective sealing

In [3] Yasuhiro Shigemoto presented the development and analysis of the operational characteristics of a new UBE 6-Roller vertical roller mill (model UM43.6SR), specifically designed for the high-efficiency grinding of slag and cement at large-capacity plants. The key innovation lies in the use of a 2-Way System scheme, where additional Sub-Rollers mechanically compact and de-aerate the material bed on the grinding table. This process is critical for preventing vibrations during the grinding of ultra-fine powders, as it increases the coefficient of friction of the material, which, according to research, also correlates with a reduction in the grinding bed thickness. The new design involves using smaller but more numerous rollers (six instead of four), which allowed for significant mill size reduction (down-sizing) while maintaining or exceeding its productivity. The key conclusions confirm the success of the development is the 6-roller VRM demonstrated a productivity increase of ~3% and a reduction in specific energy consumption of ~2% compared to the previous 4-roller model. Technical optimization ensured a 20% reduction in mill weight and a 20% reduction in foundation mass, which significantly lowers capital expenditures. Furthermore, the implemented Modular Design Concept allows for the standardization of key components, including roller modules and gear reducers, for various vertical roller mills within the plant, enhancing their reliability and reducing operational costs for maintenance and spare parts.

In work [3], the authors focused on determining the machine's efficiency level and identifying the main sources of losses using the Six Big Losses method for subsequent development of corrective measures. Based on data processing results, the average Overall Equipment Effectiveness (OEE) value for the VRM machine was 64.52%, which is significantly lower than the world standard set by the Japan Institute of Plant Maintenance at 85%. Specifically, Availability showed the lowest index at 68.84% (compared to the 90% standard), while Performance was 95.67% (compared to the 95% standard), and Quality was 97.96% (compared to the 99% standard). The analysis of the Six Big Losses indicated that the largest losses were caused by Equipment Failure Loss (Breakdowns) in the availability factor, accounting for 1684.02 hours or 75% of the total loss time. The application of the Ishikawa Diagram (Causal Diagram/Fishbone Diagram) and 5W+1H analysis identified the key root causes: ineffective planning of preventive maintenance (PM) and a low level of operator qualification/training. Recommended solutions include developing an effective PM schedule and conducting training to enhance personnel skills.

In [5] Caroline Woywadt analyzed innovative design solutions for vertical roller mills, focusing on the Modular Mill with Modular Drive System and the Swing Mill concept. The technical innovation of the Modular Mill, developed for power up to 12,000 kW, lies in the implementation of active redundancy through the use of 4-6 independent roller modules and a distributed drive system comprising 2-6 identical drive units. Each roller module includes a cylindrical tire and a hydraulic system that ensures a constant parallel grinding gap with a flat table, optimizing the vibration level. A key conclusion is that this redundancy allows the mill to continue operation at up to 85% of rated capacity even if one roller or drive module fails, which significantly enhances plant availability. The alternative solution, the Swing Mill, is ideal for smaller production facilities, as it enables the alternating grinding of raw material and clinker in a single unit without mechanical adjustments. This concept allows for the minimization of initial capital investment.

In [6] authors focused on the research and development of an on-site installation methodology for the grinding rollers of the SLM5600 vertical roller mill. The SLM5600 mill, a key unit in 6000 t/d clinker production lines, features a design comprising a whole grinding disc and three grinding rollers. Routine maintenance, which involves replacing bearings, oil seals, and wear bushings, often leads to long and expensive downtimes due to the necessity of shipping the rollers back to the manufacturer. The developed on-site installation process details the technical assembly procedure, including critical steps such as pre-heating the grinding roller support to a temperature of 120-180°C to facilitate fitting. The method specifies using a crane to precisely lift the inner hole of the roller support to the bush and employing controlled tightening of retaining bolts to achieve the required pressure and liner position. The main conclusion is that the proposed simple and efficient field assembly method eliminates the need to return the rollers to the manufacturer for repair, significantly reducing maintenance time and costs. This methodology can be successfully applied to various models within the SLM series, enhancing the operational flexibility of cement plants.

Definition of unsolved aspects of the problem. The vertical roller mills engineering distinction lies in its capacity to facilitate the combined process of simultaneous grinding and drying of a broad spectrum of feedstocks. These materials encompass calcareous and oxide compounds (limestone, quicklime, cement raw material, bauxite, magnesite), essential industrial fillers and minerals. While the primary industrial deployment of the vrm traditionally centers on the production of cement raw meal and coal pulverization, the proven versatility of the mill design has also led to its significant and successful utilization throughout the broader mining and metallurgical industries.

Problem statement.

Improving the designs of vertical roller mills to enhance the efficiency of cement and slag grinding through the optimization of working elements and the reduction of energy consumption.

Basic material and results.

Today, vertical roller mills are gradually taking a leading position in cement production and metallurgy due to their high efficiency in the grinding process. They enable the grinding of cement, slag, and other materials with minimal energy consumption. The use of slag in the cement industry contributes to increasing the strength of construction materials and significantly reduces CO_2 emissions, which helps preserve natural resources and improves the environmental sustainability of the industry.

The operating principle of a vertical roller mill is shown in Figure 1. Material is fed through a supply chute into the center of the rotating grinding table (8), which is driven by a gearbox (10), and is distributed under the rollers (5) by centrifugal forces. The rollers form a layer of material and grind it. To protect against wear, the grinding table is equipped with liner plates (7), and the rollers are equipped with tires (bands). The ground material flows over the edge of the table, after which a hot air flow through the nozzles (13) lifts it to the separator (2). Here, the finished product passes through the rotor (1), while coarse particles return through the funnel (3) to the mill for re-grinding. Excessively large particles are discharged through the chute (12) and transported for further processing. The rollers are mounted on axles installed on rocker arms (6). Hydraulic cylinders (9) are used to provide the necessary crushing force between the rollers and the table during grinding.

The grinding process in vertical roller mills is based on compression and shear within the material layer. The stress distribution in the layer facilitates the formation of micro-cracks, which ensures energy-efficient particle size reduction compared to ball mills.

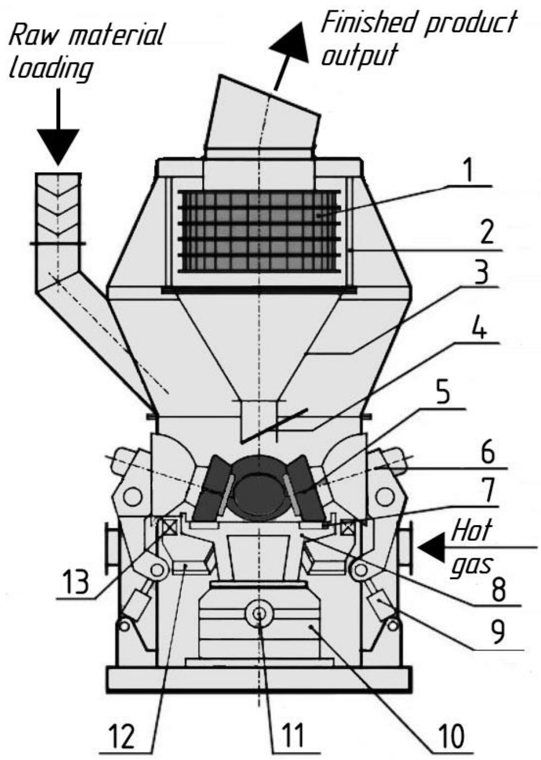

Figure 1 – Construction of a vertical roller mill

The process of comminution within vertical roller mills is fundamentally based on the combination of compression and shear mechanisms acting within the material bed situated between the working elements. This generates a multifactorial influence of contact stresses that leads to the initiation of micro-cracks within the particle/grain structure of the material. This approach ensures an efficient transfer of mechanical energy to the object of grinding and, consequently, significantly enhances the energetic efficiency of the process when compared to traditional ball mills, which primarily implement impact comminution.

Figure 2 presents the generalized fundamental schematics illustrating the structural design and spatial mutual arrangement of the principal grinding elements in medium-speed vertical roller mills. The constructive features of these mills can vary substantially depending on the equipment manufacturer. Specifically, differences exist in the geometrical parameters and configuration of the grinding table, the design and quantity of the rollers, and the types of devices that provide the necessary clamping/pressing force between the rollers and the table, which can be hydraulic, pneumatic, or hybrid mechanisms.

The primary components of the comminution unit (Fig. 2) are the rotating grinding table (2), whose surface is typically protected by wear-resistant armor/lining (3), and the rollers (1) or spherical rolling bodies (balls) (7), which execute a rotational or rolling motion across the working surface of the table. The orientation of the grinding table surface and the rollers can vary depending on the mill's design configuration: it may be horizontal (Fig. 2, a, d, e, f), low-angle inclined (Fig. 2, b), or steeply inclined (Fig. 2, c). Furthermore, there is a variability in the geometry of the contact surface of the grinding bodies: it can be smooth (Fig. 2, a, b, c, d) or possess a toroidal profile (Fig. 2, e), which influences the pressure distribution conditions and the intensity of wear.

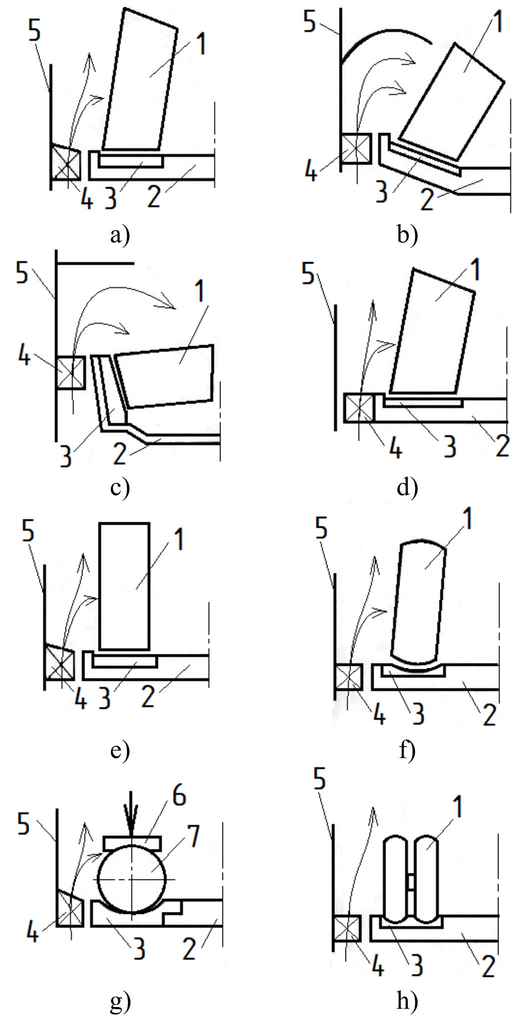

Figure 2 – Main schemes of grinding elements in vertical roller mills: 1 - Roller; 2 - Table; 3 - Armor plate; 4 - Air supply devices; 5 - Mill housing; 6 - Pressure ring; 7 - Balls

To facilitate the pneumatic conveying of the ground product and maintain the required aerodynamic conditions in the comminution zone, an air supply is mandated. Air is introduced through guide nozzles (4), which can be installed either on the stationary housing (5) of the mill (Fig. 2, a, b, c, d, f) or directly integrated into the construction of the rotating grinding table (2). This configuration contributes to the intensification of the material separation process and its discharge from the working zone, which is a critical condition for the effective operation of a vertical roller mill.

The structural diversity of rollers and grinding tables in vertical roller mills is determined both by the technical requirements of the comminution process and the manufacturers' drive to optimize resource conservation, wear resistance, and the operational efficiency of the units. The rollers can have cylindrical, conical, spherical, or toroidal shapes, which dictates the nature of their contact with the grinding table and, consequently, influences the load distribution in the grinding zone.

Cylindrical rollers ensure uniform contact with the flat table surface, typical for standard mill configurations, achieving a stable material layer compression process. Conical rollers are used to compensate for shear stresses and improve the material's discharge toward the air intake or separation zone. Spherical and toroidal rollers (Fig. 2, e) provide a variable contact pressure, allowing for more flexible regulation of the roller's penetration depth into the material layer, especially when processing materials with different mechanical properties (cement clinker, granulated slag, etc.). The roller surface can be either smooth or profiled. Profiling improves the material's gripping and transport conditions in the grinding zone and reduces the likelihood of slippage between the working surfaces. Some modifications incorporate the use of removable armor plates or segmental wear-resistant liners, which significantly facilitates maintenance and repair.

The grinding table is also characterized by a variety of forms and surface types. The most common is a flat or slightly inclined surface with radial grooves or channels that promote uniform material distribution beneath the rollers. Steeply inclined tables (Fig. 2, c) achieve additional gravitational acceleration for product transport to the periphery, improving separation conditions. The toroidal table shape ensures increased contact pressure in the central zone, which can be advantageous when intensive comminution of hard particles is required. The material used for the table and rollers is typically high-alloy steel with applied wear-resistant coatings or cladding layers. This ensures the necessary wear resistance under high specific loads and abrasive wear in conditions of continuous operation.

It should be noted that modern mills utilize both fixed and floating roller designs, which allow compensation for load unevenness and adaptation to the varying properties of the material being ground. Hydraulic roller pressing systems may include pressure sensors and automated actuators, enabling the maintenance of optimal grinding parameters in real-time.

Thus, the modern structural solutions in the design of rollers and grinding tables for vertical roller mills result from thorough engineering analysis and consideration of the processed materials' specific characteristics, ensuring not only grinding efficiency but also the longevity and reliability of the equipment's operation.

Table 1 presents typical configurations of the grinding units in vertical roller mills from leading manufacturers, along with their comparative technical specifications. This table illustrates modern approaches to the engineering design of mills intended for the fine grinding of cement and slag. The deployment of diverse configurations and technical solutions facilitates the adaptation of the mills to the specifics of the feedstock, the required productivity, energy efficiency, and the target product fineness.

Table 1 – Typical Design Configurations of Vertical Roller Mills by Leading Manufacturers

Manufacturer	Model (Series)	Number of Rollers	Roller Type	Grinding Table Type	Pressurization System	Table Diameter, mm	Design Features
LOESCHE (Germany)	LM 46.2+2C / LM 56.3+3C	2+2 or 3+3	Conical / Toroidal	Grooved, Horizontal	Hydraulic	up to 5600	Dual operating mode capability: primary + auxiliary rollers
Gebr. Pfeiffer (Germany)	MVR 5000 C-4 / MVR 6000 C-6	4 or 6	Cylindrical / Spherical	Inclined with Armor Lining	Mechano-Hydraulic	up to 6000	Independent drives for each roller, active load adjustment
FLSmidth (Denmark)	OK™ 42-4 / OK™ 56-6	4 or 6	Spherical	Smooth, Horizontal	Hydraulic	up to 5600	High energy efficiency, integrated material separation
Ube Machinery (Japan)	UM43.6 / UM48.4	4	Cylindrical	Radially Grooved	Hydraulic	up to 4800	Combined table drive, offset material feeding center
ThyssenKrupp Polysius (Germany)	QUADROPOL QMC	4	Conical	Toroidal Surface	Electro-Hydraulic	up to 5000	Separate adjustment for each roller, minimized wear

Table 2 – Comparative analysis of the efficiency and wear performance of various VRM working elements under typical operational conditions

Indicator / operating condition	Loesche lm-series	Gebr. Pfeiffer mvr	Flsmidth ok™ mill	Ube um-series	Polysius quadropol
Typical specific energy consumption for clinker grinding, kwh/t	22–26	21–25	20–24	24–27	23–26
Specific energy consumption for granulated slag grinding, kwh/t	25–30	24–28	23–27	27–31	25–29
Average roller wear rate for clinker grinding, g/t	6–9	4–7	5–8	7–10	6–9
Average table wear rate for clinker grinding, g/t	5–7	4–6	5–7	6–8	5–7
Wear rate for granulated slag grinding, g/t	8–12	6–10	7–11	10–14	8–12
Operational stability with materials of varying hardness	High	Very high	High	Medium	High
Separation efficiency	High	Very high	Very high	Medium	High
Intensity of thermal load on working elements	Medium	Low	Medium	Elevated	Medium
Suitability for high-moisture slag	Good	Excellent	Excellent	Medium	Good

As shown, conical rollers are better suited for load distribution and adaptation to the material layer thickness, whereas spherical rollers ensure uniform contact and exhibit reduced wear when processing hard materials. Regarding the grinding table, horizontal surfaces enable a more stable material distribution, while inclined or toroidal designs promote additional mixing and enhanced discharge of the comminuted material. It should be noted that all leading manufacturers utilize hydraulic or combined (mechanohydraulic) systems, which allow for flexible control of the pressure exerted on the material layer. In modifications featuring independent drives (e.g., Gebr. Pfeiffer), supplementary control over the grinding process is provided for each roller individually. Furthermore, a number of manufacturers integrate separators, automatic pressure and temperature control systems, which substantially improves the quality of the finished product and reduces energy consumption.

Table 2 provides a comparative analysis of the operational efficiency and wear intensity of the grinding components of vertical roller mills under typical operating conditions for the comminution of cement clinker and granulated blast-furnace slag. The data are summarized based on open technical literature from manufacturers and typical equipment specifications.

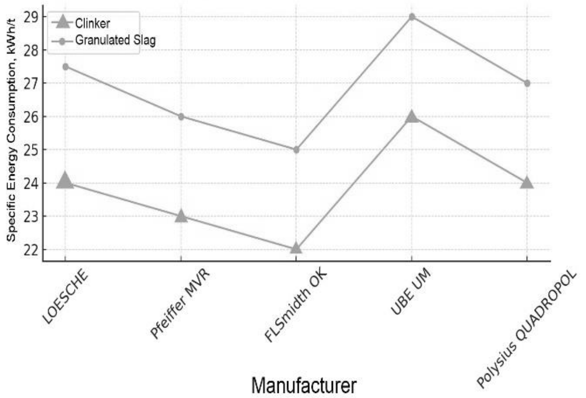

Figure 3 – Comparison of Energy Consumption during the Grinding of Clinker and Granulated Slag

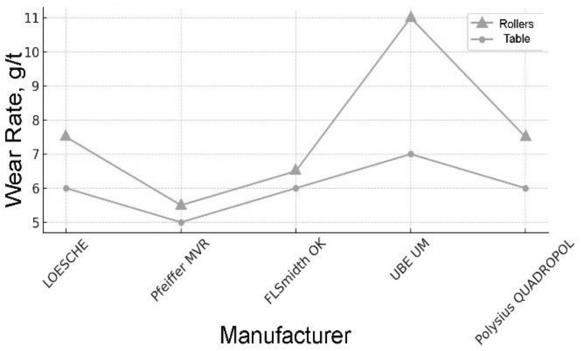

Figure 4 – Comparison of Wear Rate of Rollers and Grinding Table

The analytical conclusions drawn from the table data highlight several key performance metrics and design characteristics across different vertical roller mills. The FLSmidth OK™ and Pfeiffer MVR mills exhibit the lowest specific energy consumption, which is directly attributed to their optimized aerodynamic design and the integration of high-efficiency separators. Conversely, the Gebr. Pfeiffer MVR mill demonstrates the lowest wear rate for grinding rollers and table segments. This superior wear resistance is achieved through several technological features, namely: the independent loading mechanism for each grinding roller, the capability for precise pressure adjustment, and the use of segmental wear plates (armor segments) fabricated from materials with enhanced hardness. In contrast, the UBE mills register the highest wear rate. This increased abrasion is typically correlated with the specific design features of their rollers and a less sophisticated load distribution system. The Loesche mill models, particularly those featuring 2+2 or 3+3 roller configurations with stabilizing auxiliary rollers, present an excellent balance between energy efficiency and wear resistance. Finally, the Polysius QUADROPOL mill is noted for its high operational reliability and moderate wear characteristics, establishing it as a versatile solution applicable to a broad spectrum of material types.

Fig. 5 presents a selection matrix for vertical roller mills, which is predicated on the raw material type, its Mohs hardness index, inherent moisture content, throughput specifications, and the granulometric distribution (fineness) criteria for the resulting comminuted product. This matrix is structured in a format deemed appropriate for integration within a scholarly or technical manuscript.

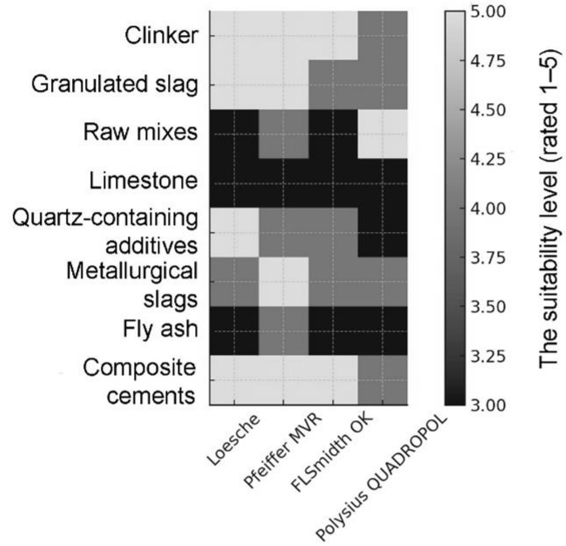

Figure 5 – VRM selection matrix contingent upon the raw material type

The presented matrix clearly demonstrates key distinctions in the selection criteria for vertical roller mills utilized for the grinding of cement clinker versus granulated blast-furnace slag. For cement clinker, characterized by its high hardness (Mohs 6–7) and low inherent moisture content (0.5–1.5%), the priority is given to mill designs (such as FLSmidth OK, Gebr. Pfeiffer MVR) that ensure high energy efficiency and the maintenance of a stable material bed. The optimal configuration typically involves 4–6 spherical or conical rollers paired with a horizontal smooth table, which serves to minimize operational wear and abrasion. Conversely, granulated slag mandates a significantly higher fineness of grind (up to 6000 cm^2/g) while processing material with an elevated moisture content (6–12%). This necessity dictates the application of specialized mill versions (e.g., Loesche LM C-series) employing conical or toroidal rollers and corresponding tables. Such a specialized configuration is critically essential for ensuring enhanced material circulation kinetics and the optimal stabilization of the slag layer, which are indispensable conditions for effective ultrafine comminution.

The derived data indicate a significant divergence in the requirements for vertical roller mills utilized for the comminution of cement raw materials (i.e., limestone, clay, and marl) compared to those required for grinding clinker and slag. The primary characteristics governing the selection for the raw mix are the low inherent hardness and the elevated natural moisture content (typically 8–15%), which together constitute the critical selection criteria for the processing equipment.

For the specified operational conditions handling raw materials such as limestone, clay, and marl which are characterized by lower hardness and high inherent moisture - mills such as the Polysius QUADROPOL, Ube UM, or Pfeiffer MPS are recommended. These machines are structurally adapted to operate effectively with high material moisture content and are designed to integrate the drying process directly into the comminution cycle. The required product fineness for these raw materials is quantified by the residue percentage on a 90µm sieve (typically 12-18%), which represents a less stringent requirement compared to the Blaine fineness needed for finished cement product.

Conclusions.

The analysis of modern vertical roller mill designs highlights a crucial engineering focus on enhancing energy efficiency and operational reliability in fine grinding processes, particularly for challenging materials like granulated slag. The fundamental distinction of VRMs lies in their energy-efficient comminution mechanism based on compression and shear within the material bed, offering a significant advantage over traditional impact-based mills.

Comparative performance data confirm that optimized aerodynamic design and sophisticated load distribution systems, which enable precise control over the grinding pressure, directly correlate with the lowest specific energy consumption and reduced wear rates of the working components. The selection of the optimal VRM configuration is shown to be highly contingent on the raw material type, where specialized designs are necessary for processing high-moisture slag to achieve the required ultrafine product fineness. This underscores that continuous technological optimization of structural elements and integrated control systems is paramount to meeting the increasing efficiency and sustainability demands of the modern construction industry.

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Особливості вибору конструкції вертикальних валкових млинів

Аннотація. Стаття присвячена аналізу специфічних аспектів вибору конструкції вертикальних валкових млинів (ВВМ), які є ключовим обладнанням у сучасній цементній, гірничодобувній та енергетичній промисловості, особливо для гранульованого шлаку. У роботі висвітлено зростаючі вимоги до енергоефективності та продуктивності технологічних процесів, що стимулює дослідження вдосконалення конструктивних елементів ВВМ, таких як валки, помельні столи та сепаратори. Особливу увагу приділено оптимізації геометричних параметрів та підвищенню зносостійкості робочих елементів, які функціонують в умовах інтенсивного абразивного та ударного зносу.
Проаналізовано сучасні інноваційні конструктивні рішення від провідних виробників, що спрямовані на підвищення надійності та зниження експлуатаційних витрат, включаючи багатороликові схеми та модульні конструкції з активною резервацією. Детально розглянуто принцип роботи ВВМ, який базується на енергоефективному подрібненні матеріалу шаром за рахунок стиснення та зсуву, на відміну від ударного принципу кульових млинів.
Наведено узагальнені схеми основних помельних елементів, які демонструють варіативність конфігурацій, включаючи різну орієнтацію столів (горизонтальну, похилу) та геометрію валків (циліндричну, конічну, сферичну). Визначено, що конструктивна різноманітність спрямована на оптимізацію розподілу навантаження, покращення захоплення матеріалу та адаптацію до особливостей сировини, зокрема, високої вологості шлаку. Аналітичний порівняльний огляд технічних характеристик та показників зносу свідчить про значну перевагу деяких конструкцій в енергоспоживанні та зносостійкості завдяки оптимізованій аеродинаміці та незалежним системам регулювання тиску.

Ключові слова: вертикальні валкові млини, гранульований шлак, констркутивні елементи, продуктивність млинів.

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