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Review on: Filters in Cement Industry

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ABSTRACT

This paper examines the history, methodology, and technological advancements in cement production, with a focus on recent innovations and the environmental impact of the industry. It provides an in-depth review of the cement production process, its energy efficiency, and associated costs, with particular attention to the use of filters for pollution control. Various types of filters commonly used in the cement industry are discussed, including Cyclones, Electrostatic Precipitators (ESPs), Fabric Filters (Bag Filters), Hybrid Filters, Jet-Pulse Filters, Multicyclones, and Packed Bed Filters. The paper highlights the effectiveness of fabric filters in capturing fine particulate matter, ensuring compliance with strict emission standards, and functioning independently of gas conditions. Additionally, the paper addresses the environmental challenges of cement production, particularly CO_2 emissions from fossil fuel combustion and limestone calcination, and explores alternative fuels such as tire-derived fuel (TDF) and plastic waste (PW) as potential solutions. Furthermore, the paper analyzes the economic aspects of filter operations, considering factors such as filter type, energy consumption, regulatory compliance, and maintenance, emphasizing the potential for cost savings and improved operational efficiency through optimized filtration systems.

1. History of the Cement Industry

The cement industry has a rich history that spans several centuries and has evolved significantly over time. Cement was invented by Joseph Aspdin, a British stonemason, who mixed ground limestone with clay and heat them in his kitchen stove, resulting in a fine powder from the concoction by pulverization. He patented Portland cement in 1824, which was produced from synthetically mixed limestone and clay, as mentioned above. The Polish cement industry began in 1857 with the establishment of the Grodziec cement plant. Today, Poland has 11 cement plants operating in a full production cycle, along with one cement grinding plant and one calcium aluminate cement plant. [1]. In Asia (1920s-1930s), the foundation of the cement industry in China can be traced back to the early 20th century. Notable figures like Liu Hongsheng played a crucial role by establishing cement and coal-briquette manufacturing enterprises, which marked the beginning of China's transition to an energy regime powered by fossil fuels. [2]. The Pakistani cement industry saw significant growth between 1991 and 1996, with a capacity utilization of approximately 89. However, demand did not grow as expected in the following years, leading to a drop in utilization to around 63% from 1997 to 2003. The industry saw a resurgence in 2004 due to a stable economy and new government projects. [3]. Back to Europe, the UK cement industry saw rapid expansion post-World War II, driven by the construction boom. By 1966, the industry had a capacity of around 18 million tonnes per year, which peaked at 20 million tonnes in the 1970s. However, capacity decreased to 13 million tonnes in the 1990s due to various industry changes. [4-5]. In Africa, the Egyptian cement industry began in 1927 with the establishment of the Tourah Portland Cement Company. This marked the start of a steady growth trajectory for the industry. [5] Over the decades, the industry has seen significant expansions. By 2008, the design capacity for clinker production was 46.6 million tonnes (Mt), which was expected to increase to 54.8 Mt by 2010. Similarly, cement production capacity was projected to rise from 46.6 Mt in 2008 to 61.8 Mt by 2010. [6] The cement industry is a substantial economic factor in Egypt, contributing 3.7% to the country's gross domestic product (GDP). This sector has continued to invest in new facilities and expand existing

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production plants to meet the growing demand driven by population growth and infrastructure projects. [7] Egypt has also become a significant player in the global cement market. In 2004, the country reached its peak in cement exports, with about 12.1 Mt of cement exported. [6]. By the 1960s, global trends had established five fundamental types of Portland cement: ordinary, rapid-hardening, low-heat, sulfate-resisting, and modified cements. These classifications have remained significant in the industry. [8]

2. Modern Era and Environmental Concerns

The Indian cement industry has shown remarkable growth since 1980, expanding from an installed capacity of 24 million tonnes to over 410 million tonnes today. This growth is attributed to liberalization policies and the industry's significant role in the economy. [9]. The cement industry is a major consumer of raw materials and energy, contributing significantly to CO_2 emissions. Efforts to make the industry more environmentally friendly include the use of alternative fuels and materials, co-processing of waste, and the development of sustainable concrete technologies. [10-13]. The cement industry in the EU is a vital economic sector, producing over 230 million tonnes annually. The industry is highly energy-intensive, and efforts are being made to increase energy efficiency and reduce fuel consumption. [14]. The US cement industry has become increasingly dependent on imports, with their share of imports in total cement consumption rising significantly since 2003. The industry is also focusing on sustainable practices to reduce its environmental footprint. [15-16]. Research is ongoing to develop eco-friendly cement and concrete materials that reduce CO_2 emissions. Innovations include the use of supplementary cementitious materials, alternative binders, and carbon capture technologies. [17-18]. The cement industry worldwide is working toward sustainability by improving energy efficiency, reducing emissions, and utilizing waste materials in production processes. [19-20]. The cement industry has a long and complex history, marked by significant growth, technological advancements, and ongoing efforts to address environmental challenges. Calcium oxide (CaO, Lime), silicon dioxide (SiO_2, Silica), and aluminum oxide (Al_2O_3, Alumina) are essential components for cement. The lime came from a lime-containing raw material called calcareous, and other oxides from a clayey or argillaceous material. Silica sand, iron oxide (Fe_2O_3), and aluminum hydroxide ($Al(OH)_3$) are supplemental raw materials that may be applied in order to archive the requirements of the composition. Gypsum is another mandatory raw material, which is required to burn in the cement clinker during the grinding process to regulate the cement's setting time. In the place of calcium carbonate, there will be a combined process with sulfuric acid using anhydrite or calcium sulfate, and also can be made as Portland cement. Sulfuric acid is derived from sulfur dioxide, which was originally produced in the flue gases in the burning process.

3. Cement Production Process

Cement production process is complicated and energy-intensive process that involves several key stages as;

3.1. Raw Material Extraction and Preparation

Raw Materials: The primary raw materials used in cement production are limestone, clay, and other materials such as shale and sand. [21-23]

Grinding: The raw materials are ground into a fine powder, known as raw meal, which is crucial for the subsequent stages. [21, 24]

3.2. Clinker Production

Preheating and Calcination: preheat of the raw meal before feeding it into a kiln, where it undergoes calcination at temperatures ranging from 700-900°C. This process produces clinker, the key component of cement. [21, 25]

Kiln System: The kiln system, including the pre-calciner, is responsible for the majority of fuel consumption and CO2 emissions in cement production. [25-26]

3.3 Clinker Cooling and Grinding

Cooling: After exiting the kiln, the clinker is rapidly cooled to preserve its reactive properties. [21]

Grinding: To produce cement, mix the cooled clinker with gypsum and other additives, then grind it into a fine powder [21-24].

4. Energy Consumption and Environmental Impact

4.1 Energy Use: Cement production is highly energy-intensive, primarily relying on fossil fuels such as coal and natural gas [25, 27-28]

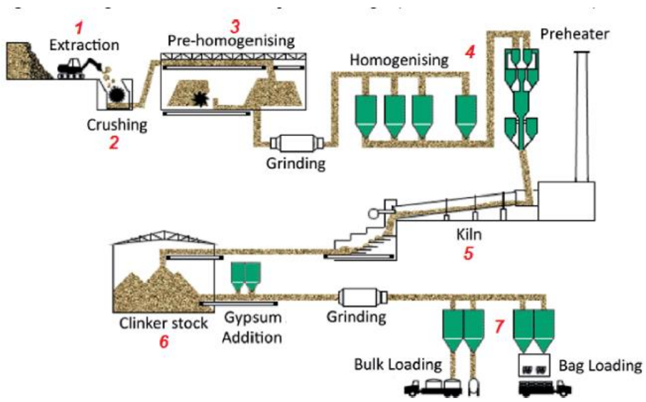
4.2 CO_2 Emissions: The process is a significant source of CO_2 emissions, mainly due to the calcination of limestone and the combustion of fossil fuels. [22-23, 25]

4.3 Alternative Fuels: To mitigate environmental impact, alternative fuels such as tire-derived fuel (TDF) and plastic waste (PW) are being explored. [25, 28]

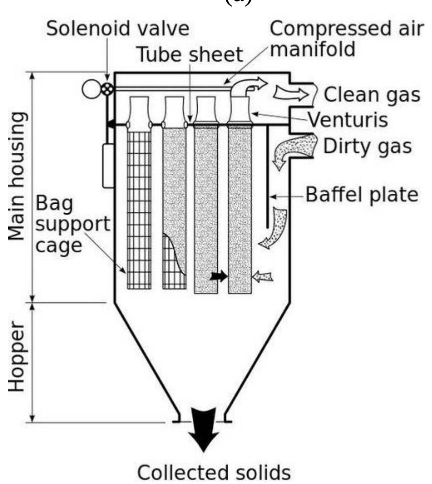
5. Cement production process

Cement production process, as presented in Figure 1.a, starts from raw material extraction from mines (1st process) and transported to the stone crushers for crumbling (2nd process). Raw materials are crumbled to about 25 mm in diameter and stockpiled in stock halls, picked up by moving cranes and carried to raw mills for grinding (3rd process). The final product is called farine and the products are stockpiled in farine stocks (4th process). Farine enters to rotary kiln after pre-heater and is heated up to 1400–1450ºC (5th process). Semi-finished product exiting the rotary kiln is called clinker and cooled down in the cooler and stockpiled in the clinker stock. Clinker is ground with different types of additive mixtures for producing different types of cement (6th process). The final product is stockpiled according to its types and then is sent to the marketplace as bagged or bulk cement (7th process).

The cement process industries utilizing raw materials for the production of cement and these raw materials are burnt in the kiln at the temperature around 1400°C. During cement manufacturing process air gets pollute which includes particulate matter NOx, SOx., CO, CO_2, hydrocarbons and other substances are released to the atmosphere. The burning of organic material such as coal oil wastes in kilns produces an exhaust gas. CKD pollute the environment by about 800 kg per each ton of the produced cement. Collecting / capturing this CKD is very important for environment in addition to supplying it to other industries like streets treatment and covering by asphalt. Currently most factories are using what is called electric bag (Figure 1.b) composite dust collector (huge number in special housing named "dust collector bag house".



(a)



(b)

Figure 1: Schematic for; (a) cement production process, (b) bags filter housing

6. Technological and Process Optimizations

6.1 Automation and Control Systems: Implementing advanced control systems and automation can optimize energy consumption and improve process efficiency. [27]

6.2 Dry Process: Transitioning to a dry cement production method can significantly reduce fuel consumption and CO_2 emissions. [23]

6.3 Alternative Raw Materials: The use of alternative raw materials and supplementary cementing materials, such as metakaolin and industrial byproducts, can enhance sustainability and reduce environmental impact. [29-30]

Sustainability Measures:

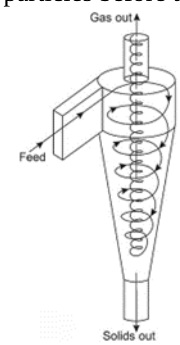
6.4 Emission Reduction: Efforts to reduce emissions include the use of alternative fuels, improving energy efficiency, and capturing emissions. [29, 31]

6.5 Resource Efficiency: Co-processing industrial wastes and using alternative raw materials can reduce the extraction of natural resources and enhance waste management [29, 32].

7. Types of filters were utilized in the cement industry

7.1 Cyclones

Cyclones (Figure 2) are mechanical separators that use centrifugal force to remove dust particles from gas streams. That, it commonly used for pre-separation of large dust particles before they enter more efficient filters. [33-35].



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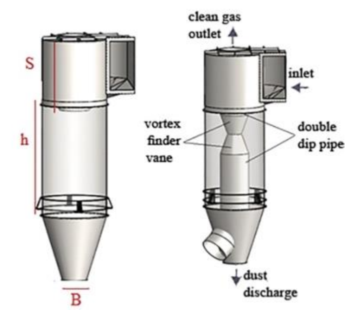

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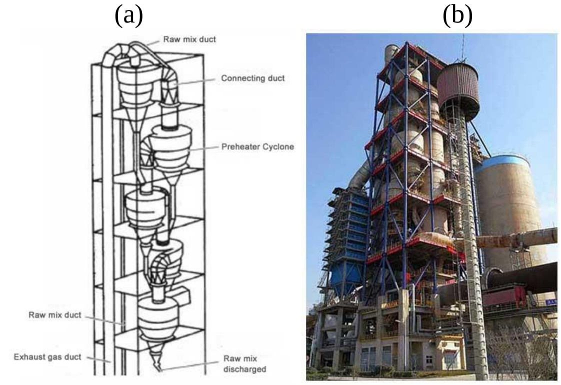

(c)

Figure 2: Cyclones; (a) schematic and parts, (b) cement cyclone preheater structure (c) real image of cement cyclone preheater structure.

7.2 Electrostatic Precipitators (ESPs):

ESPs use electrical charges to attract and capture dust particles on collection plates via three stages; particle charging, transport, and collection. ESPs are effective for high-temperature gases and large volumes of dust. The flue gas loaded with fly ash is sent through pipes having negatively charged plates which give the particles a negative charge. The particles are then routed past positively charged plates, or grounded plates, which attract the now negatively charged ash particles. The particles stick to the positive plates until they are collected. With limitation on its performance, that it can be affected by variations in gas temperature and dust resistivity. [34-36] ESPs are used for the collection of dusts, mists and fumes; (a) Dust: solid particles from 0.1 to 100 µm in diameter, (b) Mist: liquid droplets suspended in a gas, and (c) Fume: solid or liquid particles formed by condensation from a vapor.

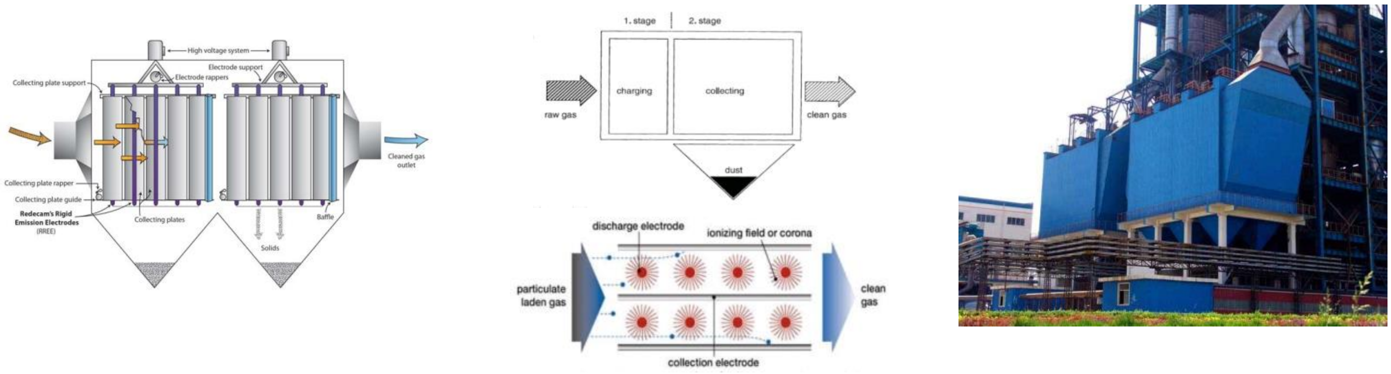

Figure 3: Electrostatic Precipitators (ESPs)

7.3 Fabric Filters (Bag Filters)

These filters use fabric bags (Figure 1.b) to capture dust particles as gas passes through them. Its high efficiency in capturing fine particles, are in compliance with stringent emission standards, and independence from gas conditions. Cement Filter Bag has extremely high particle removal efficiency; durable with long lifespan up to 9 months. The common materials include used are; PTFE, polyester, and polyimide, which offer resistance to high temperatures, humidity, and chemical corrosion. [34, 37-39]

7.4 Hybrid Filters:

Combine the principles of ESPs and fabric filters to optimize dust collection. It was recommended to be used in scenarios where both high efficiency and adaptability to varying conditions are required. [33-34]

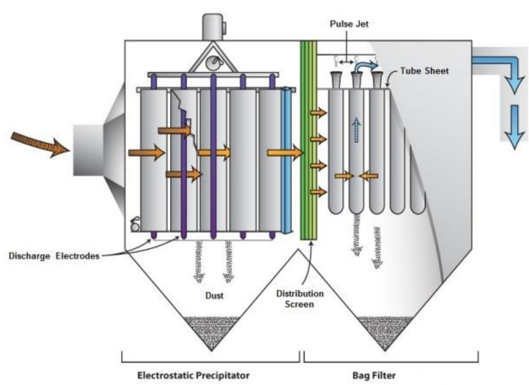

Figure 4: Hybrid filter schematic

7.5. Jet-Pulse Filters:

A type of fabric filter that uses short bursts of compressed air to clean the filter bags. Its effective cleaning mechanism can maintain filter efficiency and prolongs bag life. [34, 40].

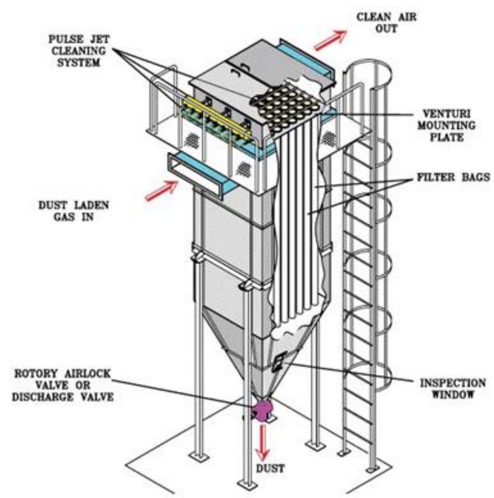

Figure 5: Hybrid filter schematic

7.6. Multicyclones and Packed Bed Filters:

Multicyclones use multiple small cyclones in parallel, while packed bed filters use a bed of granular material to capture dust. Which is often used in high-temperature environments like clinker coolers. [36, 41]

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8. Innovative and Specialized Filters:

8.1 PTFE Composite Filters: Offer high resistance to temperature, humidity, and chemical corrosion, making them suitable for harsh cement plant conditions. [37]

8.2 Natural Fiber Filters: Sisal fiber-based filters coated with nanoparticles for improved dust adsorption and environmental sustainability. [41]

8.3 Cement-Based Filters: Novel materials for pollutant removal, particularly in wastewater treatment applications. [43-44].

9. Efficiency comparison of cement filters:

Several types of cement filters and their particulate matter (PM) removal efficiencies can be compared as;

9.1 Bottom Ash-Sand Mixtures

Efficiency of this type of filters with 50:50 bottom ash-sand mixture demonstrated removal rates of 58.05% for 1.8 µm particles, 93.92% for 10 µm particles, and 92.45% for 60 µm particles. [45] The advantages like; consistent and stable particulate matter removal over time were recorded. While it requires field validation with actual pavement systems.

9.2. Electrostatic and Centrifugal Filters

Combined electrostatic and centrifugal cleaning achieved over 90% efficiency, with at least 50% efficiency for ultra-fine particles (0.3-1 microns). [46] High efficiency for a wide range of particle sizes is considered as its major advantage. On the other hand, it is considered complex and demanding operating conditions.

9.3. Porous Ceramic Membranes (PCMs)

It achieved efficiency nearly 100% removal for 3-10 µm particles, 99.2% for 1.0 µm, 95.0% for 0.5 µm, and 91.6% for 0.3 µm particles. [47] Its high porosity, low pressure drops, and excellent corrosion resistance are its main advantages. But it requires specific binder composition and sintering temperature for optimal performance.

9.4. Quartz Sand Filters

It achieved more than 99% removal efficiency for cement dust. [48] Enhanced efficiency was recorded with pre-loaded dust and low initial penetration. It requires periodic cleaning to maintain efficiency.

9.5. Meta-Aramid/Polysulfone-Amide (PMIA/PSA) Composite Nanofibrous Membranes

It was reported that, this type of filters showed removal efficiency of 96.7% for 0.1 µm, 98.3% for 0.2 µm, and 99.6% for 0.3 µm particles, [49] With excellent thermal stability and mechanical retention. That make it suitable for high-temperature applications. The efficiency of particulate matter (PM) removal by cement filters is influenced by several key factors, which can be categorized into filter design, operating conditions, and particle characteristics. Here are the main factors identified in literature.

10. Filter Design and Structure

The type of filter media, such as fibrous filters or porous ceramic membranes, significantly impacts PM removal efficiency. For instance, fibrous filters with specific fiber arrangements and solid volume fractions (SVF) can enhance filtration performance. [50] Similarly, porous ceramic membranes with a spherical α-Al_2O_3 coating have shown high efficiency in removing PM of various sizes. [47]

- The thickness of the filter layer and the grain size of the filter media are crucial. Thinner layers and finer grains generally improve PM capture efficiency. [51]
- Advanced designs, such as the use of electrostatic precipitators and multi-functional filter bags, can enhance PM removal. Electrostatic charges can improve particle deposition on filter media, reducing pressure drop and increasing efficiency. [52-53]

11. Operating Conditions

The velocity of the gas flow through the filter and the resulting pressure drop are critical parameters. Higher flow velocities can increase the removal efficiency but may also lead to higher pressure drops, which need to be managed [50, 54]

The ability to regenerate filters and maintain their performance over time is essential. Filters that can be easily regenerated or have high clogging resistance tend to maintain higher efficiency. [51, 55]

12. Particle Characteristics

The size of the particles being filtered affects removal efficiency. That, filters are generally more efficient at capturing larger particles, while ultrafine particles pose a greater challenge. [47, 46]

While, the concentration of particles in the gas stream before filtration can influence the filter's performance and its operational lifespan. High concentrations may lead to quicker clogging and reduced efficiency. [46]

13. Environmental and Operational Factors

Factors such as humidity and temperature can affect the performance of filters. For example, high humidity can lead to particle agglomeration, which might enhance or hinder filtration efficiency depending on the filter type. [56]

In addition, the presence of other pollutants, such as nitrogen oxides (NOx), can interact with PM and affect the overall removal efficiency. Technologies that address multiple pollutants simultaneously, such as catalytic filters, can be more effective. [53]

14. Economics comparison of cement filters:

The operation of cement filters, such as electrostatic precipitators (ESPs) and fabric filters, is crucial for controlling dust emissions in cement plants. The economics of these operations can be influenced by several factors, including initial investment, operational costs, maintenance, and compliance with environmental regulations. To evaluate the operation of cement filters in the context of environmental regulations, several key financial factors need to be considered:

14.1. Capital Investment:

Installing additional control devices such as selective non-catalytic reduction systems, wet flue gas desulfurization units, and activated carbon filters can be capital intensive. [57] That, upgrading to modern technologies like cyclones, bag filters, and electrostatic filters to reduce dust emissions also requires significant capital investment. [35]

14.2. Operational and Maintenance Costs:

Maintaining compliance with environmental regulations involves continuous operation and maintenance costs for the installed pollution control equipment. [57] The type of filter media used can impact the overall performance and maintenance costs. For example, low drag filter media can improve performance and reduce the total cost of ownership. [58]

14.3. Energy Consumption:

The energy consumption of the cement plant is a significant variable cost. Technologies like medium voltage variable speed drives (VFDs) can help in reducing energy consumption and CO2 emissions, thus lowering operational costs. [59] Therefore, utilizing alternative fuels and improving energy efficiency can mitigate the environmental impact and reduce costs associated with energy consumption. [60]

14.4. Environmental Compliance Costs:

Non-compliance with environmental regulations can result in fines and penalties, which can be financially burdensome. [57] That, the financial burden of health impacts due to pollutants like PM2.5 can be substantial. For instance, in Rio Branco do Sul, the indirect health costs attributable to PM2.5 were estimated at $1.4 million. [61]

14.5. Economic Incentives and Funding:

Adequate government funding, incentives, and R&D efforts are crucial for adopting innovative and emerging technologies like Carbon Capture and Storage (CCS). [60] That, implementing Environmental Accounting (EA) can help in internalizing external costs and improving financial performance by reflecting environmental costs in financial statements. [62]

14.6. Market Dynamics:

The evolution of cement products from commodities to differentiated products can influence market dynamics and financial planning. [63] Where, a detailed cost analysis, including layout requirements and time schedules, is essential for determining the most practical and cost-effective solutions. [64]

To assess the economic viability of cement filters in meeting environmental standards, several key financial metrics and methodologies are used. These metrics help in evaluating both the economic performance and the environmental impact of the cement production process. The following financial metrics and methodologies provide a comprehensive framework for assessing the economic viability of cement filters in meeting environmental standards, ensuring that both economic and environmental factors are considered in decision-making processes.

15. Life Cycle Cost (LCC)

LCC involves calculating the total cost of ownership over the life of an asset, including initial costs, operation, maintenance, and disposal costs. Therefore, LCC is used to assess the economic burdens of different strength grades of cement manufacturing, showing that higher strength grades have slightly better economic performance despite greater environmental impacts. [65]

16. Full Cost Accounting

This includes the sum of Life Cycle Assessment (LCA) costs and LCC, providing a comprehensive view of both economic and environmental costs. Thus, full cost accounting is used to compare the costs of different types of cement, such as ordinary Portland cement and Portland blast-furnace slag cement, highlighting the economic implications of increased slag content. [66]

17. Environmental Cost Accounting (ECA)

ECA integrates environmental costs into traditional financial accounting, helping to identify and internalize externalities. Where, ECA can reflect positively on the profitability of industrial companies by encouraging the internalization of environmental costs through legislation and government intervention. [62]

18. Cost-Benefit Analysis (CBA)

CBA evaluates the total expected costs versus the benefits of a project or decision. That, CBA is a critical tool in environmental decision-making, helping to balance ecological protection with economic development. [67]

19. Emergy Accounting

Emergy accounting assesses the performance of resource utilization and environmental emissions by quantifying the energy used in production processes. This method is used to evaluate the sustainability level of cement production, focusing on nonrenewable resource input and economic investment. [68]

20. Economic Evaluation Criteria

These criteria include metrics such as production costs, profitability, and efficiency of resource use. Evaluating the economic performance of cement plants involves analyzing production costs, deviations in production capacities, and the impact of technical developments on economic outcomes. [69]

21. Types of Filters and Their Costs:

21.1 Electrostatic Precipitators (ESPs)

These are dependent on raw gas temperature and the electrical resistance of dust particles, which can fluctuate with temperature and humidity. While effective, their performance can be inconsistent, leading to potential higher operational costs due to variability in efficiency. [34]

21.2 Fabric Filters (Bag Filters)

These are gaining preference due to their ability to comply with lower emission limits and their independence from operating conditions. They are particularly effective during plant start-up and shutdown phases, which can reduce overall operational costs. [34, 70]

21.3 Operational Efficiency and Cost Reduction

Innovations such as low drag filter media have shown to improve the performance of baghouses, leading to reduced total cost of ownership by enhancing filter efficiency and lifespan. [58] Modern jet-pulse systems allow for the use of longer filter bags, which can reduce both investment and operational costs by optimizing air tank pressure and cleaning cycles. [70].

21.4 Energy Consumption:

The largest portion of the life cycle cost (LCC) of bag filters is attributed to energy consumption, primarily from fan motors and compressed air usage. Optimizing these parameters can significantly reduce operational costs. [70] Integrating, Waste Heat Recovery (WHR) systems, with CO_2 capture technologies can further reduce energy consumption and operational costs. For instance, membrane separation processes combined with WHR systems have been shown to reduce CO_2 capture costs by up to 70% compared to conventional methods. [71]

21.5 Environmental Compliance and Economic Impact

Meeting stringent environmental regulations often necessitates the use of advanced filtration systems. While this can increase initial investment, it can also lead to long-term savings by avoiding fines and improving plant efficiency. [72] The use of alternative raw materials and fuels can reduce emissions and energy consumption, contributing to cost savings and improved environmental performance. [29]

21.6 Maintenance and Longevity:

The use of intelligent cleaning control systems and advanced filter media can extend the lifespan of filters, reducing maintenance costs and downtime. [40] Automating filter operations can enhance efficiency and reduce labor costs, as well as improve working conditions by minimizing direct contact with hazardous materials. [73]

22. Conclusions

This review provides an analysis of particulate matter abatement strategies utilized in cement production, encompassing a range of filtration technologies such as Cyclones, Electrostatic Precipitators (ESPs), Fabric Filters (Bag Filters), Hybrid Filters, Jet-Pulse Filters, Multicyclones, and Packed Bed Filters. The efficacy of fabric filtration in achieving compliance with stringent particulate emission standards, coupled with its independence from gas condition fluctuations, is highlighted. In addition, the paper addresses the significant environmental impact of cement manufacturing, particularly concerning carbon dioxide emissions originating from fossil fuel combustion and limestone calcination. The viability of alternative fuels, specifically tire-derived fuel and plastic waste, as a means of reducing these emissions is investigated.

The economics of operating cement filters are influenced by the type of filter used, innovations in filter media and cleaning systems, energy consumption, regulatory compliance, and maintenance practices. By optimizing these factors, cement plants can achieve significant cost savings and improve overall operational efficiency.

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