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Performance Analysis of Concrete Incorporating Industrial Waste for Sustainable Construction

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ABSTRACT

Concrete is the most widely used construction material; however, the extensive use of Portland cement contributes significantly to carbon emissions and natural resource consumption. One promising approach to addressing this issue is the incorporation of industrial waste as a supplementary cementitious material in concrete mixtures. This study aims to analyze the influence of industrial waste on concrete performance based on studies published over the last five years. A Systematic Literature Review (SLR) was employed by examining scientific articles retrieved through Google Scholar using predefined inclusion and exclusion criteria. The findings indicate that industrial waste can improve the concrete microstructure through pozzolanic reactions and filler effects, leading to enhanced compressive strength, improved tensile performance, reduced porosity, lower water absorption, and better durability when applied at optimum replacement levels. In addition to improving engineering performance, the utilization of industrial waste contributes to reducing Portland cement consumption, lowering carbon emissions, and promoting circular economy principles within the construction industry. Therefore, industrial waste demonstrates significant potential as an alternative material for developing sustainable concrete that fulfills both technical performance requirements and environmental sustainability objectives.

Keywords: *Concrete Performance, Industrial Waste, Supplementary Cementitious, Material, Sustainable Concrete, Systematic Literature Review.*

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1. | INTRODUCTION

Concrete is the most widely used construction material worldwide due to its advantages of high compressive strength, ease of production, good durability, and relatively low cost compared to other construction materials. The growth of global infrastructure development has led to a continuous increase in the demand for concrete year after year. However, high concrete consumption also leads to an increase in the use of Portland cement as the primary binder, which is known to contribute significantly to carbon dioxide (CO_2) emissions and energy consumption in the construction sector (Hamdi et al., 2022). This situation has driven the development of various studies focused on developing more environmentally friendly concrete materials without compromising their technical performance (Gusty et al., 2023).

The cement industry is one of the largest contributors to greenhouse gas emissions in the manufacturing sector due to the clinker calcination process and the energy requirements of its production. Therefore, various approaches have been developed to reduce cement use by utilizing alternative materials with cementitious or pozzolanic properties (Fitriyanti & Fatimura, 2019). One widely studied approach is the use of industrial waste as a supplementary cementitious material (SCM) or mineral additive in concrete mixes. Utilizing industrial waste not only has the potential to reduce cement consumption but also supports more sustainable waste management through the concept of a circular economy.

Various types of industrial waste have been reported to contain silica, alumina, and other reactive compounds capable of participating in pozzolanic reactions, thereby improving the microstructure of the cement paste (Hamdi et al., 2022). This reaction results in the formation of additional calcium silicate hydrate (C-S-H), which contributes to increased mechanical strength, reduced porosity, and enhanced concrete durability. In addition to functioning as a reactive material, the fine particles of industrial waste also provide a filler effect, improving the density of the concrete matrix and reducing the volume of internal voids.

However, the effect of industrial waste on concrete performance does not always show a consistent trend. Differences in the physical and chemical characteristics of waste, particle size, substitution content, water-cement ratio, and concrete curing methods can result in variations in workability, compressive strength, tensile strength, water absorption, and resistance to aggressive environments (Aris, 2023). Several studies report that using industrial waste at optimum levels can improve concrete's mechanical properties, while use exceeding the optimum limits can actually reduce performance due to reduced active cement content and increased water requirements in the mixture.

Research developments during the 2019–2023 period indicate increasing attention to sustainable concrete (green concrete) as a strategy to reduce the carbon footprint of the construction sector (Sholeh, 2023). The focus of research is no longer limited to increasing compressive strength but also includes evaluating physical properties, durability, resource efficiency, and its contribution to sustainable development. This approach positions industrial waste as a secondary resource that has added value when optimally utilized in modern concrete technology (Ahmad et al., 2021).

Hamdi et al. (2022) stated that although various studies on the use of industrial waste as concrete additives have been published, most still focus on a single type of waste or on limited testing parameters. Studies that integrate various research results to evaluate the effect of industrial waste on concrete performance as a whole are still relatively limited. However, a comprehensive understanding is needed to provide an overview of the relationship between industrial waste characteristics, concrete property improvement mechanisms, and their implications for the development of sustainable construction materials. Based on these conditions, this study aims to analyze the performance of concrete made from industrial waste based on research results published during the period 2019–2023. The analysis focuses on the effect of industrial waste use on the properties of fresh concrete, mechanical properties, physical characteristics, and durability aspects, as well as evaluating its contribution in supporting the development of more sustainable construction materials through the utilization of alternative resources and reducing the use of Portland cement.

2. | RESEARCH METHOD

This study employed the Systematic Literature Review (SLR) method to identify, evaluate, and synthesize research findings on the performance of concrete containing industrial waste. The SLR method was chosen because it provides a comprehensive overview of research developments, identifies trends in results from various studies, and identifies research gaps requiring further study (Darmawan, 2022). This approach also allows conclusions to be drawn based on published scientific evidence, thereby enhancing objectivity in the analysis process.

The research phase began with determining the focus of the study, namely the effect of industrial waste as a mineral admixture on concrete performance. A literature search was then conducted through scientific databases indexed in Google Scholar, with primary sources coming from reputable international journals and accredited national journals published between 2019 and 2023. The search process uses a combination of several keywords, including industrial waste, supplementary cementitious material, green concrete, concrete performance, mechanical properties of concrete, durability of concrete, waste utilization in concrete, as well as equivalent terms in Indonesian to obtain a wider scope of literature (Gyeyok, 2019). he obtained literature was then selected based on inclusion and exclusion criteria. Inclusion criteria included research articles discussing the use of industrial waste as an additive or partial cement substitute in concrete, presenting data on the physical, mechanical, and durability properties of concrete, published between 2019 and 2023, and available as full-text scientific articles. Articles irrelevant to the research topic, non-scientific publications, proceedings without peer review, or not providing adequate technical information were excluded from the analysis (Hamdi et al., 2022).

Articles meeting the criteria were then evaluated and classified based on the characteristics of the industrial waste used, the percentage used in the concrete mix, the testing method, and the observed performance parameters, such as workability, compressive strength, tensile strength, water absorption, porosity, and durability. The collected data were then analyzed descriptively and comparatively by comparing the results between studies to identify patterns, trends, advantages, and limitations of the use of industrial waste as a concrete additive. The results of this synthesis serve as the basis for formulating a discussion regarding the influence of industrial waste on improving concrete performance while also evaluating its contribution to supporting the development of more sustainable construction materials (Ahmad et al., 2021).

3. | RESULTS AND DISCUSSION

Literature synthesis shows that the use of industrial waste as an additive or partial cement substitute has become a major focus in the development of sustainable concrete during the 2019–2023 period. This increased attention to alternative materials is driven by the need to reduce the consumption of Portland cement, which is known to be a major contributor to carbon emissions in the construction sector. Various studies have reported that industrial waste with pozzolanic or cementitious properties can increase resource efficiency while maintaining or even improving concrete performance when used in appropriate proportions. This concept aligns with the principles of green concrete, which aims to produce construction materials with a lower environmental impact without compromising their technical quality.

Various studies have shown that the chemical and physical characteristics of industrial waste are key factors determining its successful use in concrete mixes. Materials rich in amorphous silica, alumina, and reactive calcium have the ability to react with calcium hydroxide produced by cement hydration, forming additional calcium silicate hydrate (C-S-H) compounds. The formation of this C-S-H gel causes the concrete microstructure to become denser, improves the bond between the cement paste and aggregate, and reduces the pore volume that could potentially become a pathway for water and aggressive ions to enter (Hamdi et al., 2022). In addition to the pozzolanic reaction mechanism, the finer particle size of waste compared to cement also produces a filler effect that can fill micro-voids, thereby increasing the density of the concrete matrix.

Regarding the properties of fresh concrete, most studies indicate that the addition of industrial waste affects workability. Materials with a high specific surface area generally increase water requirements due to their greater water absorption capacity than ordinary cement. Consequently, slump values tend to decrease as the admixture percentage increases. Pagalla (2023) states that some types of waste with finer particle shapes and better size distribution can actually improve mix homogeneity, so that the decrease in workability remains within acceptable limits. Therefore, optimizing the admixture proportions and using superplasticizers are often recommended to maintain workability without significantly increasing the water-cement ratio. Analysis of mechanical properties shows that compressive strength is the most frequently used parameter to evaluate the effectiveness of industrial waste as a concrete admixture. In general, most studies report an increase in compressive strength at low to moderate substitution levels, while excessive use tends to decrease strength due to a reduction in active cement content. This increase in compressive strength is primarily influenced by the formation of additional hydration products and a denser concrete microstructure. Conversely, if the amount of waste exceeds the pozzolanic reaction capacity, some of the material functions only as an inert filler, resulting in a less optimal cement hydration process. This explains why each type of waste has a different optimum content depending on its mineralogical characteristics and particle fineness (Rahayu, 2019).

In addition to compressive strength, various studies also show a tendency for increased splitting tensile and flexural strength in concrete using industrial waste in optimal proportions (Gideon, 2023). This increase is related to improved interfacial bonding (interfacial transition zone/ITZ) between the cement paste and aggregate. A denser ITZ structure reduces local stress concentrations, thus improving the concrete's ability to resist cracking. Although the increase is generally not as large as the compressive strength, these results indicate that the utilization of industrial waste not only increases the compressive capacity but also contributes to the overall mechanical behavior of concrete (Hamdi et al., 2022)

In terms of physical properties, almost all studies report a decrease in porosity and water absorption when industrial waste is used at optimum concentrations. This reduction in porosity is directly related to the filling effect of fine particles and the formation of secondary hydration products that close capillary cavities. Concrete with lower porosity generally exhibits better resistance to the penetration of water and aggressive substances from the environment (Doni, 2023). Therefore, increasing microstructural density not only increases strength but also improves the overall physical quality of the concrete.

This improvement in microstructural quality directly impacts concrete durability. Various studies have shown that concrete with industrial waste admixtures has better resistance to chloride penetration, sulfate attack, and wetting and drying cycles than conventional concrete. The reduced permeability slows the diffusion of aggressive ions, thus minimizing the risk of reinforcement corrosion. Furthermore, the formation of a denser matrix also increases resistance to damage caused by long-term environmental changes. However, the effectiveness of this increased durability is still influenced by the type of waste, the quality of the mixing process, and the concrete's post-cast curing conditions.

From a sustainability perspective, utilizing industrial waste offers dual benefits by reducing the volume of waste disposed of in the environment while simultaneously reducing the need for Portland cement. This approach supports the implementation of the circular economy concept by reusing industrial byproducts into value-added construction materials. Reduced clinker use directly contributes to lower carbon emissions and energy consumption in the cement production process. Therefore, using industrial waste as a supplementary cementitious material not only offers technical advantages but also supports the achievement of low-carbon development targets in the construction sector. Despite showing excellent prospects, the synthesis results also identified several challenges that still require attention. Pagalla (2023) stated that variations in the characteristics of industrial waste between producers result in inconsistent chemical composition and physical properties, potentially resulting in variations in concrete performance. Furthermore, not all studies use the same material characterization methods and testing procedures, limiting direct comparisons between research results. Standardization of material characterization, determination of optimum content, and evaluation of long-term durability are important aspects that still need to be developed so that industrial waste utilization can be more widely applied in the construction industry.

Overall, the literature synthesis demonstrates a consensus that industrial waste has significant potential as a concrete admixture when selected based on its material characteristics and applied in optimal proportions. The presence of pozzolanic reactions, the fine particle filling effect, and increased microstructural density are the main mechanisms explaining the improvement in mechanical properties and durability of concrete. These findings reinforce the belief that industrial waste utilization is an effective strategy in supporting the development of sustainable concrete that not only meets technical requirements but also provides environmental benefits through reduced carbon emissions and optimized resource utilization.

4. | CONCLUSION

Utilizing industrial waste as an additive or partial cement substitute is an effective approach to supporting the development of sustainable concrete. Based on a literature synthesis published between 2019 and 2023, industrial waste with pozzolanic or cementitious characteristics can improve the microstructure of concrete through the formation of additional hydration products and the filling effect of fine particles. This mechanism contributes to improved mechanical properties, particularly compressive strength, and improves the physical characteristics of concrete by reducing porosity and water absorption. Furthermore, concrete using industrial waste at optimum proportions exhibits increased durability under various aggressive environmental conditions, potentially extending the service life of structures.

The study also shows that the success of industrial waste utilization is significantly influenced by the chemical and physical characteristics of the material, the particle fineness, the percentage used, and the quality of the concrete mixing and curing process. Therefore, determining the optimum content is crucial for achieving a balance between improved technical performance and efficient binder use. Furthermore, industrial waste utilization provides environmental benefits by reducing Portland cement consumption, reducing carbon emissions, and optimizing the use of waste as a secondary resource within the circular economy concept.

Overall, the utilization of industrial waste offers excellent prospects as an alternative supporting material in modern concrete technology. Further research should focus on standardizing waste characterization, evaluating long-term durability, conducting life cycle assessments, and conducting economic feasibility studies to ensure broader application of this material in the construction industry and support more sustainable infrastructure development.

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The authors declare that there is no conflict of interest.

Ethical Approval and Originality Statement

Ethical approval was obtained for this study. The manuscript represents original work and has not been previously published, nor is it under consideration by another journal.

Data Disclosure Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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