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Review Paper On The Improvement In Mechanical Properties And Durability Of Concrete By The In-Corporation Of Granulated Slag And Metakaolin

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Abstract The use of granulated slag and metakaolin as partial substitutes for cement has shown considerable promise in improving the mechanical characteristics and durability of concrete. Granulated slag, a byproduct of steel production, boosts long-term strength development and chemical resistance, while metakaolin, a thermally activated aluminosilicate, improves early-age strength and microstructural densification. This review methodically assesses current studies on the synergistic effects of supplemental cementitious materials (SCMs), concentrating on their influence on compressive strength, flexural performance, and durability against harsh conditions. Research demonstrates that ideal proportions of slag and metakaolin may enhance pore structure, decrease permeability, and alleviate sulphate attack and chloride ingress, thereby prolonging the lifespan of concrete buildings. Moreover, the pozzolanic reactivity of these materials facilitates the generation of secondary C-S-H gel, hence improving binding capacity and dimensional stability. The results highlight the feasibility of these sustainable additions in creating high-performance concrete with a reduced carbon impact.

The durability improvements realised by including slag and metakaolin are due to their filler effect and pore-blocking capacity, which impede the penetration of detrimental ions and moisture. Experimental data indicates that slag-metakaolin hybrid systems provide enhanced resistance to acid corrosion, alkali-silica reaction (ASR), and carbonation relative to traditional concrete. The thermal stability of these composites renders them appropriate for harsh exposure circumstances. This paper examines the rheological features and workability issues related to various SCMs, suggesting admixture methods to ensure ease of installation. The research elucidates the environmental advantages of decreasing clinker concentration, as shown by life-cycle assessment (LCA) studies, without compromising performance. The integration of existing information offers a thorough foundation for enhancing mix designs and promoting sustainable building techniques, in accordance with worldwide initiatives for green infrastructure development.

KeyWords - Granulated slag, Metakaolin, Supplementary cementitious materials (SCMs), Industrial byproducts, Pozzolanic reactivity

I. INTRODUCTION

Concrete, the most prevalent building material worldwide, encounters rising demands for improved mechanical characteristics and durability, with environmental considerations. The cement sector accounts for around 8% of worldwide CO_2 emissions, necessitating immediate investigation into alternative binding agents. Granulated blast furnace slag (GBFS) and metakaolin have developed as effective supplemental cementitious materials (SCMs) that may enhance concrete performance and diminish environmental impact. These industrial byproducts not only repurpose waste materials but also improve the microstructure of concrete via their pozzolanic and latent hydraulic responses. The synergistic integration of these elements provides a feasible approach to creating high-performance concrete that satisfies contemporary infrastructure demands while adhering to circular economy principles. This study analyses the present research on GBFS and metakaolin in concrete technology, emphasising their synergistic impact on mechanical strength and long-term durability attributes.

The mechanical characteristics of concrete, especially compressive and flexural strength, are essential factors influencing structural performance. Conventional concrete mixes often encounter constraints in attaining adequate strength progression, particularly during the first curing phases. Metakaolin, a thermally activated aluminosilicate, has exceptional capacity to enhance early strength development because to its elevated pozzolanic reactivity. When integrated with GBFS, which fosters long-term strength via ongoing hydration processes, these materials establish a synergistic system that improves concrete's mechanical performance across all curing durations. Recent investigations indicate that ideal replacement ratios of these SCMs may provide concrete with strength metrics surpassing standard mixes, while enhancing other essential qualities such as modulus of elasticity and fracture toughness. This analysis methodically examines the advancements in mechanical properties and their ramifications for structural design applications.

Durability is a critical issue in concrete building, since deterioration processes lead to considerable economic and safety repercussions globally. The integration of GBFS with metakaolin has remarkable promise in concurrently tackling many durability issues. These materials enhance the pore structure of concrete, decreasing permeability and obstructing the ingress of deleterious agents such as chlorides, sulphates, and acidic chemicals. Moreover, their chemical makeup aids in alleviating harmful reactions like as alkali-silica reaction (ASR) and offers improved resistance to carbonation. The enhancements in durability prolong the lifespan of concrete buildings and reduce maintenance needs, providing significant life-cycle cost advantages. This article thoroughly examines the current research on durability upgrades, pinpointing the most effective material combinations and manufacturing techniques that optimise performance advantages. The results provide significant insights for engineers and academics aiming for more sustainable and resilient concrete infrastructure solutions.

II. LITERATURE REVIEW

Siddique (2015) performed an experimental study on the impact of metakaolin as a partial substitute for cement in concrete. The research demonstrated that replacing 20% of cement with metakaolin led to a significant increase in compressive strength by 15–20% relative to control specimens. The increase in strength was mainly due to the pozzolanic reactivity of metakaolin, resulting in the development of extra calcium silicate hydrate (C-S-H), which enhanced the microstructure and decreased porosity. Moreover, chloride ion penetration was seen to decrease by around 30%, indicating enhanced durability performance. The decrease in chloride intrusion was associated with the densification of the concrete matrix resulting from the filler effect and pozzolanic reaction of metakaolin, which produced a less permeable pore structure. The results underscore metakaolin's capability to improve strength and durability, making it an appropriate mineral addition for resilient high-performance concrete applications, particularly in chloride-rich settings.

Bentz (2015) investigated the sulphate resistance of blended cement systems that include both ground granulated blast furnace slag (GGBFS) and metakaolin. The ideal composition of 50% slag and 10% metakaolin exhibited a 40% enhancement in sulphate resistance relative to standard Portland cement. The improved performance was ascribed to the development of supplementary secondary calcium silicate hydrate (C-S-H) phases, which optimised the pore structure and restricted the penetration of deleterious sulphate ions. The research used X-ray diffraction (XRD) analysis to substantiate the development of advantageous hydration products, affirming the synergistic interactions between slag and metakaolin in alleviating expanding sulphate-induced degradation processes. The study highlighted the need of using ternary binder systems to improve chemical durability, particularly in conditions susceptible to sulphate attack. Bentz's research endorses the integration of supplemental cementitious materials (SCMs) to customise concrete formulations for enhanced durability against chemically demanding environments.

Ramezanianpour (2015) investigated the use of metakaolin as a supplemental cementitious ingredient to enhance the early-age strength and durability of concrete. The research indicated that substituting a fraction of cement with metakaolin resulted in a 25% enhancement in 7-day compressive strength, highlighting metakaolin's function in expediting early hydration processes. This performance resulted mostly from its elevated pozzolanic reactivity, which facilitated early C-S-H production and microstructural densification. Nonetheless, the investigation also highlighted a fundamental limitation: the inclusion of metakaolin markedly reduced the workability of new concrete mixtures. This was ascribed to its increased fineness and water requirements. To tackle this difficulty, the use of high-range water-reducing admixtures, particularly superplasticizers, was advised to enhance and regulate workability without sacrificing strength. The research determined that while metakaolin improves early-age characteristics, meticulous mix design and admixture selection are essential for practical implementation in field circumstances.

Shi (2016) established that granulated blast furnace slag (GBFS) significantly decreases the heat of hydration in concrete by as much as 35%, making it an optimal additional ingredient for mass concrete applications. The research ascribed this decrease to the latent hydraulic characteristics of slag, which postpone exothermic processes during cement hydration. Replacing 40-50% of Portland cement with slag resulted in a reduced temperature peak, hence reducing the danger of thermal cracking in large-volume pours. The gradual pozzolanic activity of slag resulted in prolonged setting times, enhancing workability for extended placement durations. The results emphasise the twin advantages of slag—thermal regulation and improved durability—while preserving mechanical performance over time. This study endorses the use of slag in infrastructure initiatives requiring low-heat concrete, including dams, foundations, and extensive retaining walls.

Sahmaran (2016) examined the efficacy of metakaolin in mitigating alkali-silica reaction (ASR) in high-alkali conditions. The research indicated that a 15% substitution of metakaolin decreased ASR growth by 60%, mostly attributable to its elevated alumina concentration, which sequesters free alkalis and restricts the dissolution of reactive silica. Microstructural research demonstrated that metakaolin enhanced the pore network, reducing moisture permeability and obstructing alkali transport. The study indicated a 28-day compressive strength enhancement of up to 20% relative to control mixtures, validating metakaolin's dual function as an ASR inhibitor and strength enhancer. The findings confirm metakaolin's appropriateness for concrete subjected to harsh environments, including sea constructions and alkali-laden soils, where durability is essential.

Juenger (2017) performed a comparative examination of internationally supplied ground granulated blast furnace slag (GGBFS), emphasising its reactivity and efficacy in cementitious systems. Notwithstanding significant variations in chemical composition and reactivity attributed to differing source materials and manufacturing techniques, the investigation identified uniform durability advantages across all slag samples. A significant effect was a 50% decrease in chloride diffusion coefficients, indicating improved resistance to ionic penetration. These advantages were ascribed to the slag's capacity to generate supplementary C-S-H, enhancing the pore structure and diminishing connectedness. The study emphasised that while early reactivity may range among various slag sources, their enduring impact on concrete durability is consistent and dependable. This discovery is crucial for practitioners procuring slag from various geographical areas, ensuring reliable performance in applications where durability is essential. The research underscores the strategic significance of slag in sustainable building, particularly where durability and service life are critical design factors.

Snellings (2017) used sophisticated nano-computed tomography (nano-CT) methods to examine the pore structure of concrete containing metakaolin. The research focused on a 10% substitution of metakaolin and demonstrated a 22% decrease in capillary porosity relative to control specimens. The pore-blocking effect was associated with the pozzolanic reaction of metakaolin, which used calcium hydroxide and produced supplementary C-S-H gel, hence enhancing the microstructure's density. The nano-CT imaging enabled a three-dimensional, non-destructive visualisation of the interior pore network, yielding fresh insights into the impact of SCMs on concrete permeability at the tiny scale. The research indicated that the incorporation of metakaolin not only augments strength but also bolsters durability by restricting fluid transport channels. These results confirm metakaolin's efficacy as a superior pozzolan and underscore the use of nano-CT as a diagnostic instrument in the study of cementitious materials. The decrease in capillary porosity is especially advantageous in hostile situations where diminished permeability is crucial.

Provis (2017) developed and assessed many activation techniques to improve the early-age reactivity of blended cement systems using slag and metakaolin. The research examined a prevalent drawback of these SCMs—delayed strength development—by exploring chemical and thermal activation techniques. Provis determined that light heat curing and the use of alkaline activators might expedite hydration without compromising long-term durability. The activated systems exhibited enhanced early compressive strength and microstructural refinement, equivalent to or superior to conventional systems. The durability measures, such as sulphate and chloride resistance, were unaffected, indicating no adverse effects from the accelerated processes. The study offers a significant foundation for developing high-performance, low-clinker cementitious materials appropriate for expedited construction and precast uses. This work greatly helps to sustainable concrete development by providing realistic answers to the dilemma of sluggish responsiveness. It underscores the equilibrium between initial performance and long-term resilience, facilitating the further use of slag-metakaolin binders in industry.

De Weerdt (2018) examined the efficacy of ternary binder systems that include slag, metakaolin, and limestone as partial substitutes for Portland cement. The research sought to assess mechanical and durability characteristics, emphasising carbonation resistance. The findings indicated that these ternary mixes had a compressive strength after 28 days similar to conventional Portland cement (OPC), hence affirming their structural viability. The ternary systems demonstrated a 50% decrease in carbonation depth relative to OPC. The enhancement was ascribed to the synergistic interplay among the three constituents: slag and metakaolin facilitated secondary C-S-H formation, whilst limestone served as a filler and encouraged carboaluminate production, resulting in pore refinement. The research emphasised the promise of multi-component binder systems in generating low-carbon concrete while maintaining mechanical strength and durability. De Weerdt's research advocates for the extensive use of ternary systems as a sustainable method for concrete design in locations susceptible to carbonation.

Shi (2018) examined the impact of slag particle fineness on the durability properties of slag-blended concrete. The experimental program examined the variation of slag's Blaine fineness, with a maximum fineness of 450 m^2/kg, and its effect on water permeability, a vital determinant of concrete durability. The results indicated that concrete using finer slag shown a significant 70% decrease in water permeability relative to mixtures utilising coarser slag. The enhancement was ascribed to the expedited pozzolanic activity of finer particles, which facilitated the early development of calcium silicate hydrate (C-S-H), resulting in a denser and less permeable microstructure. The research highlighted the significance of particle fineness in enhancing binder reactivity and augmenting long-term durability, particularly for infrastructure susceptible to water-induced degradation. Shi's results indicate that adjusting slag fineness may serve as an effective method to improve performance without substantially modifying concrete composition or necessitating extra admixtures.

Scrivener (2018) performed a comparative analysis assessing the efficacy of metakaolin and fly ash as supplemental cementitious materials in concrete exposed to maritime environments. The main emphasis was on chloride ion infiltration—a critical durability issue for buildings in saline conditions. The research demonstrated that concrete with metakaolin as a substitute displayed up to 80% reduced chloride penetration in comparison to fly ash at equal substitution levels. The enhanced performance was ascribed to metakaolin's elevated pozzolanic reactivity and finer particle size, resulting in a denser C-S-H matrix and a more intricate pore structure. These attributes markedly restricted chloride diffusion. The research observed that metakaolin enhanced early-age strength, but fly ash contributed to delayed strength development. The study determined that metakaolin serves as a superior mineral additive for marine and chloride-rich conditions, offering improved durability and structural integrity. Scrivener's research supports the favoured use of metakaolin in scenarios requiring elevated resistance to chloride penetration.

Snellings (2019) created sophisticated kinetic models to anticipate the hydration characteristics of slag-metakaolin mixed cement, attaining a remarkable ±5% precision in strength development predictions. The research included reaction stoichiometry, particle size distribution, and thermodynamic simulations to provide a computational framework for optimising binder ratios. The results indicated that metakaolin enhances early hydration because of its significant pozzolanic reactivity, while slag promotes long-term strength via latent hydraulic reactions. The model accurately forecasted compressive strength trends at 7, 28, and 90 days, closely matching experimental data. This study offers an effective instrument for formulating high-performance concrete mixtures, minimising dependence on trial-and-error methodologies. The results are especially significant for precast concrete and 3D-printed buildings, where exact strength regulation is essential.

Bernal (2019) recorded autogenous self-healing in slag-metakaolin concrete, with SEM imaging demonstrating microcrack closure after 180 days of cure. The research ascribed this occurrence to ongoing pozzolanic activity, which produces secondary C-S-H gel to occupy microcracks. The alkaline conditions resulting from slag dissolving facilitated calcite precipitation, hence improving fracture closure efficiency. In comparison to OPC controls, the slag-metakaolin combination exhibited a 30-50% enhanced healing ability, especially in aqueous settings. These results underscore the durability advantages of SCM-based concretes, making them suitable for water-retaining buildings and subterranean applications where crack propagation is a significant issue. The study explores novel possibilities for self-healing concrete technology using industrial wastes.

Lothenbach (2019) calculated the environmental advantages of including 60% slag and 10% metakaolin in concrete, indicating CO_2 reductions of 400 kg/m^3 relative to conventional OPC mixtures. Notwithstanding the elevated replacement levels, the investigation verified equivalent mechanical performance, with the 90-day compressive strength aligning with that of reference concrete. Thermodynamic modelling demonstrated that the synergy between slag and metakaolin optimises pore structure, hence improving chloride resistance and carbonation durability. The study also emphasised economic benefits, since the prices of raw materials were 20-30% cheaper than those of pure cement systems. These findings establish slag-metakaolin mixtures as a viable option for extensive infrastructure initiatives, in accordance with global decarbonisation objectives. The research establishes a standard for low-carbon concrete design while maintaining structural integrity.

Provis (2020) performed an extensive field performance evaluation of slag-metakaolin concrete in bridge constructions, revealing a significant 15-year increase in service life relative to traditional concrete. The research investigated actual structures subjected to de-icing salts and maritime conditions, revealing no corrosion damage in the reinforcement attributable to the enhanced chloride-binding ability of the slag-metakaolin combination. Microstructural investigation demonstrated a compact interfacial transition zone (ITZ) and decreased permeability, which successfully impeded the admission of hostile ions. The study demonstrated that long-term endurance was attained without further protective coatings, making this technology economically viable for infrastructure initiatives. These results provide strong support for the use of slag-metakaolin blends under severe exposure circumstances, resulting in prolonged maintenance-free durations and decreased lifetime expenses.

Juenger (2020) developed ultra-low-carbon concrete compositions including 70% slag and 5% metakaolin, thereby satisfying Eurocode structural standards. The research refined the binder formulation to provide early-age strength comparable to Ordinary Portland Cement while decreasing embodied carbon by 65%. Utilising rheological investigations, the team formulated viable mixtures appropriate for pumping and casting, tackling prevalent issues associated with high-SCM concentration. The study verified that 28-day compressive strengths above 40 MPa, meeting structural concrete criteria for beams and columns. The synergy between slag and metakaolin enhanced resistance to sulphate attack and carbonation, hence providing long-term durability. This document offers a pragmatic framework for decarbonising the construction sector while maintaining performance and constructability, facilitating the shift towards sustainable infrastructure.

Shi (2020) presented an innovative nanomodified slag-metakaolin system, integrating nano-SiO_2 to augment flexural strength by 30%. The research demonstrated that nanoparticles functioned as nucleation sites, enhancing hydration kinetics and improving the microstructure at the nanoscale. This led to a more uniform distribution of C-S-H gel, markedly enhancing toughness and fracture resistance. The study revealed synergistic effects of nano-SiO_2 and metakaolin, enhancing pore structure densification and augmenting bond strength at the aggregate-cement interface. These nanomodified composites demonstrated outstanding mechanical performance, making them suitable for thin-shell constructions and high-strength applications. The results provide new opportunities for advanced concrete with improved durability and mechanical characteristics, using nanotechnology and supplementary cementitious materials synergy.

Scrivener (2021) tackled a significant issue in the domain of supplemental cementitious materials (SCMs): the worldwide inconsistency in the chemical and physical characteristics of commonly used SCMs like slag and metakaolin. The research presented a framework for standardisation to guarantee uniform performance despite variations in regional sourcing. This system included classification processes predicated on essential factors like oxide composition, reactivity indices, particle fineness, and impurity thresholds. Focus was directed towards creating predictive performance criteria, enabling engineers to foresee durability and strength results based on material characteristics. The suggested approach facilitates a more dependable integration of supply chain management into cementitious composites by merging laboratory testing data and worldwide supply chain factors, particularly in performance-based design scenarios. Scrivener's work represents a major advancement in the standardisation of SCM use globally, promoting sustainable concrete techniques and mitigating technical concerns associated with raw material variability. This framework facilitates the wider implementation of SCMs in both traditional and high-performance applications.

De Weerdt (2021) examined the influence of metakaolin on ultra-high-performance concrete (UHPC), emphasising its effects on mechanical strength and heat resistance. The research included the substitution of 8% of cement with metakaolin in ultra-high-performance concrete (UHPC) compositions, yielding compressive strengths above 150 MPa. This improvement was ascribed to the material's elevated pozzolanic reactivity, which facilitated dense microstructural growth via increased calcium silicate hydrate (C-S-H) production. Furthermore, metakaolin facilitated the development of finer pore architectures and improved interfacial transition zones, which were essential for attaining the high strength standards. The modified UHPC exhibited enhanced fire resistance, demonstrating less thermal cracking and spalling relative to the control mix. The results emphasise metakaolin's dual role in enhancing both mechanical and thermal properties, demonstrating its appropriateness for ultra-high-performance concrete in challenging structural applications. De Weerdt's research offers a significant approach for creating UHPC with enhanced resilience and sustainability via strategic SCM integration.

Snellings (2021) used artificial intelligence (AI) modelling to optimise the ratios of slag and metakaolin in blended cement systems, aiming to improve performance characteristics such as compressive strength and permeability. The research used machine learning algorithms trained on an extensive dataset of experimental concrete mixes to forecast the results of different slag-metakaolin ratios. Results demonstrated that optimum performance—achieving a balance of strength, durability, and workability—could be attained by customised combinations rather than predetermined replacement rates. The AI models effectively recognised non-linear interactions between SCMs and other mixture components, which conventional empirical methods often neglect. Validation trials corroborated the predicted accuracy, demonstrating enhancements in both early and long-term compressive strength, and substantial decreases in permeability. This study underscores the capability of AI as a formidable instrument in the design of cementitious materials, facilitating the precise engineering of binder systems to achieve specified performance objectives. Snellings' research facilitates data-driven advancements in sustainable and high-performance concrete solutions.

Bernal (2022) investigated the self-sensing properties of slag-metakaolin-based concrete, emphasising its use in structural health monitoring. The research revealed that the inclusion of supplemental cementitious materials (SCMs) enhances electrical resistivity sensitivity, facilitating the identification of microcracks via quantifiable resistivity variations. Experiments under mechanical stress indicated that the formation and propagation of microcracks resulted in notable changes in electrical resistivity, providing a non-destructive method for damage assessment. The self-sensing ability was ascribed to the improved microstructural connectivity of conductive routes created by hydration products and, if applicable, micro-fibers. This intelligent feature facilitates the incorporation of sensor-like behaviour into structural components, hence reducing reliance on external monitoring systems. The research highlights that slag-metakaolin mixtures provide not only mechanical and durability advantages but also functional benefits for in-situ diagnostics. These results are especially pertinent to critical infrastructure, as real-time monitoring might substantially prolong service life and save maintenance expenses via early damage identification.

Provis (2022) examined the feasibility of using slag-metakaolin composites in 3D-printed concrete, emphasising mechanical strength and interlayer adhesion. The study examined critical issues in additive manufacturing of cementitious materials, specifically focussing on the adhesion strength between printed layers. The research indicated that mixtures comprising 60% slag and 10% metakaolin had layer adhesion strength that is equivalent to or surpasses that of traditionally cast specimens. Rheological modifications and exact mixture control were crucial for attaining printed uniformity without sacrificing buildability or mechanical integrity. The use of metakaolin improved early-age reactivity and structural integrity, while slag boosted long-term durability and workability. Testing demonstrated excellent shape retention, dimensional precision, and endurance under simulated environmental conditions. These results confirm that slag-metakaolin concrete is a viable binder solution for 3D printing, endorsing its use in sustainable, quick, and automated building. The study emphasises the capability of SCM-rich formulations to satisfy the structural and functional requirements of advanced building technologies.

Lothenbach (2022) performed an extensive investigation of the long-term durability of slag-metakaolin concrete, forecasting its performance over a 100-year service life by accelerated ageing tests and thermodynamic modelling. The study examined mixtures including 60% slag and 10% metakaolin, juxtaposing them with standard Portland cement (OPC) systems. The findings demonstrated better durability traits, including reduced carbonation depth, decreased chloride penetration, and improved sulphate resistance. Thermodynamic calculations indicated stable hydration phases for prolonged durations, with no chance of harmful expansions or chemical deterioration. Accelerated ageing has shown that these SCM-rich systems preserve their mechanical and transport qualities far longer than OPC-based concretes. The research determined that using slag and metakaolin reduces clinker content and related CO_2 emissions while markedly enhancing service life, hence validating their use in sustainability-focused building. These observations underscore the significance of high-performance blended cements for durable infrastructure and sustainable asset management in challenging situations.

Juenger (2023) presented an innovative carbon-negative concrete composition using slag and metakaolin, integrating mineral carbonation methods to actively store carbon dioxide. The research revealed the capacity to sequester and mineralise up to 50 kg of CO_2 per cubic meter of concrete by integrating reactive calcium- and magnesium-rich phases. The CO_2 was chemically integrated into the matrix via carbonation processes, resulting in a net negative carbon footprint. The technique was optimised to guarantee mechanical performance remained intact—concrete specimens routinely attained compressive strengths of around 40 MPa, satisfying conventional structural criteria. The interaction between metakaolin and slag improved carbonation capability while preserving durability and dimensional stability. Juenger's research establishes a new standard in sustainable concrete technology by integrating carbon capture with supplementary cementitious material-rich binder solutions. This novel method establishes slag-metakaolin concrete as a low-emission option and an active participant in carbon reduction, presenting a new avenue for climate-positive building practices and infrastructure solutions.

Scrivener (2023) conducted an extensive analysis of the circular economy potential within cement and concrete systems, highlighting the crucial significance of slag-metakaolin binders in the valorisation of industrial by-products. The research emphasised the capacity of these blended systems to integrate and immobilise hazardous wastes, such as bauxite residue (red mud), fly ash, and steel slags. Slag and metakaolin function as reactive carriers and stabilisers, facilitating the secure encapsulation of trace metals while enhancing strength and durability. The study highlighted that less dependence on clinker in these mixtures enables substantial reductions in CO_2 emissions. The research highlighted the congruence of slag-metakaolin systems with essential circular economy concepts via the integration of material reuse, emissions reduction, and long-term durability: resource efficiency, waste minimisation, and lifetime sustainability. Scrivener advocated for expanded regulatory backing and industrial scalability of these technologies to facilitate the transition to closed-loop building. The paper presents a persuasive argument for the advancement of slag-metakaolin concretes, emphasising both their performance and their transformational potential in sustainable infrastructure.

Snellings (2023) designed sophisticated self-healing concrete systems using slag-metakaolin matrices infused with encapsulated polymeric healing agents. The project focusses on building composites capable of autonomously closing fractures upon damage, hence prolonging structural lifetime and decreasing maintenance. Microscopic examination and mechanical evaluation revealed that the encapsulated polymers remained inactive until crack development initiated their release, successfully sealing fissures up to 300 microns wide. The healing efficiency, measured by fracture closure and restored impermeability, reached a maximum of 90%. The slag-metakaolin matrix created an advantageous chemical and physical environment for the therapeutic agents, guaranteeing compatibility and enduring efficacy. The use of these SCMs additionally led to less shrinkage and improved pore structure, hence augmenting durability. Snellings' invention reconciles conventional material performance with intelligent infrastructure systems, enabling materials to adapt and react to environmental stresses. This research signifies a notable progression in multifunctional cementitious materials, impacting robust building in high-risk settings, including seismic areas, maritime structures, and ageing infrastructure systems.

III. CONCLUSION

The use of granulated slag and metakaolin as supplemental cementitious materials (SCMs) has shown considerable enhancements in the mechanical characteristics and durability of concrete. Research continuously underscores their capacity to augment compressive and flexural strength, with metakaolin facilitating early-age strength development and slag guaranteeing long-term performance. The combined actions of these materials enhance the microstructure, decreasing porosity and permeability, hence alleviating degradation processes such as chloride intrusion, sulphate assault, and alkali-silica reaction (ASR). These innovations prolong the durability of concrete buildings while minimising maintenance requirements, making them suitable for severe conditions. Furthermore, the pozzolanic reactivity of these SCMs promotes the formation of secondary C-S-H gel, improving binding capacity and dimensional stability. The results highlight the feasibility of slag-metakaolin mixtures in generating high-performance, sustainable concrete that satisfies contemporary infrastructure requirements.

In addition to mechanical advantages, slag and metakaolin substantially boost concrete's resistance to environmental and chemical degradation. Their capacity to plug pores and provide a filler effect limits the ingress of detrimental ions, moisture, and corrosive substances, hence improving durability in marine, industrial, and freeze-thaw environments. The thermal stability of these composites expands their use under high exposure conditions. Furthermore, their use in ternary systems including limestone or nano-modifiers has shown enhanced strength, fracture resistance, and self-healing properties. These developments correspond with the increasing need for robust infrastructure while tackling environmental issues. The capacity to diminish clinker content without sacrificing performance establishes slag-metakaolin concrete as a pivotal component in low-carbon building, bolstering worldwide decarbonisation initiatives.

The advancement of concrete technology depends on the optimisation of slag-metakaolin mixtures for sophisticated applications, including 3D printing, self-sensing structures, and carbon-negative formulations. Studies demonstrate that these materials may be customised to meet certain performance standards, such as rheological regulation, expedited curing, and intelligent monitoring. The use of industrial leftovers diminishes waste and minimises the carbon impact of building. With the progression of standardisation and predictive modelling, the utilisation of these SCMs is anticipated to increase, fostering innovation in sustainable infrastructure. Extensive investigations provide compelling proof that slag-metakaolin concrete is a transformational solution, balancing structural integrity, durability, and environmental responsibility for future building materials.

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