Review of Silica Fume and Metakaolin as Partial Cement Replacements in Fiber-Reinforced Concrete

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ABSTRACT

This review aims to provide a comprehensive analysis of the effects of silica fume and metakaolin as partial replacements for cement in fiber-reinforced concrete (FRC). The use of supplementary cementitious materials (SCMs) has gained significant attention in recent years as a means to enhance the mechanical and durability properties of concrete while reducing its environmental impact. Silica fume and metakaolin are two commonly used SCMs that have shown promising results in various concrete applications. The review begins by discussing the fundamental properties and characteristics of silica fume and metakaolin, including their pozzolanic reactivity and particle size distribution. Subsequently, the influence of incorporating these SCMs on the fresh and hardened properties of FRC is examined. The mechanical properties, such as compressive strength, tensile strength, and flexural strength, are evaluated in light of the varying replacement levels of silica fume and metakaolin. Additionally, the review addresses the durability aspects of FRC with silica fume and metakaolin, focusing on resistance to chloride ion penetration, carbonation, and alkali-silica reaction (ASR). The microstructural changes, hydration characteristics, and pore structure evolution of FRC mixes incorporating these SCMs are also discussed.

INTRODUCTION

Concrete's high mechanical strength, long lifespan, and low production cost make it a popular construction material worldwide. Traditional concrete, however, has shortcomings like weak tensile strength and brittleness. The use of fibers to reinforce concrete can remedy these issues. Incorporating fibers into concrete creates a composite material with all the advantages of concrete plus toughness, ductility, and increased resistance to cracking.

When silicon and ferrosilicon alloys are manufactured, silica fume is a byproduct. As a highly reactive pozzolan with a large surface area, it is ideal for improving the characteristics of concrete. The addition of silica fume to concrete can increase the material's toughness and longevity while also making it easier to work with. In contrast, metakaolin is a pozzolan made by calcining kaolin clay at very high temperatures. It is a highly reactive substance, similar to silica fume, that can enhance the qualities of concrete.

The purpose of this study is to examine the possibility of using silica fume and metakaolin as cement substitutes in fiber-reinforced concrete. Fiber-reinforced concrete and its advantages will be introduced first in this study. After that, it'll go into detail on how silica fume and metakaolin can improve concrete's performance. In the end, the study will show the outcomes of experiments conducted on fiber-reinforced concrete that partially replaced cement with silica fume and metakaolin.

Fiber-Reinforced Concrete

By incorporating fibers into the mix, the mechanical qualities of fiber-reinforced concrete are enhanced. Steel, glass, carbon, and synthetic polymers are just some of the materials that can be utilized to create FRC fibers. Typically, fewer than 5% by volume of these fibers are added to the concrete mixture.

Concrete's flexural strength, toughness, impact resistance, and fatigue resistance can all be enhanced by the incorporation of fibers. By decreasing cracking and increasing resilience to environmental degradation, fibers help increase concrete's longevity. Bridge decks, parking garages, and airport runways are just few of the many structural uses for FRC.

When kaolin clay is subjected to high temperatures during the calcination process, a pozzolan called metakaolin is created. Amorphous silica and alumina make up the bulk of this fine white powder. The strong reactivity of metakaolin and its potential to improve concrete's characteristics have made it a popular additive. As a byproduct of cement hydration, calcium hydroxide combines with metakaolin in concrete to produce calcium silicate hydrate (C-S-H) gel. Improved mechanical qualities including compressive strength, flexural strength, and durability arise from the creation of extra C-S-H gel inside the concrete matrix.

Metakaolin not only makes concrete stronger and last longer, but it also makes it easier to shape and place. The small particle size and high surface area of metakaolin result in a more cohesive concrete mix, which reduces the need for additional water and enhances the flowability of the mix. This makes metakaolin an ideal material for use in self-consolidating concrete (SCC) and high-performance concrete (HPC).

The use of metakaolin has also been linked to a less carbon footprint in the construction industry. The majority of concrete's carbon dioxide emissions come from the manufacturing of cement, the main binder. The carbon footprint of concrete can be lowered by using less cement when using metakaolin as a partial replacement. As a highly reactive pozzolan, metakaolin can increase the durability, workability, and mechanical qualities of concrete. It is ideally suited for use in high-performance and sustainable concrete applications due to its capacity to generate additional cementitious elements and increase the cohesiveness of the concrete mix.

CEMENT

Cement is a binder, a substance used in building that is used to bind together different substances by setting, hardening, and adhering to them. Cement is typically used in conjunction with aggregate, which consists of things like sand and gravel. Mortar for masonry uses cement, and concrete uses cement in combination with sand and gravel.

Cement is a very fine powder made from a variety of minerals. When combined with water, this powder makes a glue-like paste that sets rock solid. Cement's characteristics vary based on its constituent parts and the degree to which the powder has been refined.

Concrete's primary ingredient is cement. It's widely used in the building industry because of its low cost and great quality.

Building cement is often an inorganic material (lime or calcium silicate) that, depending on its capacity to set when exposed to water, is classified as either hydraulic or non-hydraulic.

CEMENT PRODUCTION

The two main ingredients in cement production are limestone and clay or shale. After being mined from the quarry and crushed into a fine powder, these raw ingredients are subsequently mixed in the appropriate quantities.

The 'raw feed' or 'kiln feed,' as it is known, is a mixture of raw materials that is heated in a rotary kiln to temperatures between 1400° C and 1500° C. At its most basic, a rotating kiln is just a long tube, up to 200 meters in length and maybe 6 meters in diameter, with a long flame protruding from one end. Raw feed is introduced into the kiln at the lower, cooler end, where it travels to the upper, hotter end and eventually falls out, where it cools.

Clinker is the name for the material that forms in the kiln. It is usually made up of rounded lumps that are between 1mm and 25mm across.

After the clinker has cooled, it can be temporarily stored in a clinker store or sent straight to the cement mill.

The clinker is turned into a fine powder by the cement mill. The clinker is usually ground up with a small amount of gypsum, which is a form of calcium sulfate. When water is added to the cement, the gypsum controls how it sets.

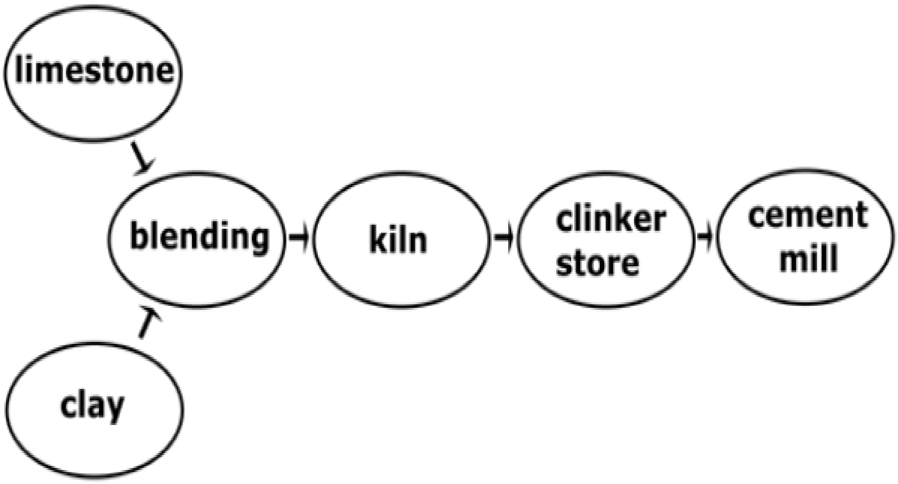

Fig. 1: Basic components of the cement production process

Need of the Study

Due to its high quality mechanical and durability features, fiber reinforced concrete (FRC) has found widespread use in the building industry. A cement base, aggregates, and fibers make up FRC. Standard concrete, however, has issues like weak tensile strength, fragility, and cracking. Fibers added to concrete can increase the material's tensile strength, ductility, and toughness, helping to solve these problems.

Concrete's characteristics can be enhanced with the help of supplementary cementitious materials (SCMs) including silica fume and metakaolin. These substances react with calcium hydroxide to produce new cementitious compounds; they have a pozzolanic composition. Porosity can be decreased and concrete's durability enhanced with the use of SCMs.

The manufacturing of silicon metal and ferrosilicon alloys generates a fine powder known as silica fume. Highly reactive particles of silica fume can increase concrete's packing density and make it easier to deal with. In addition, silica fume can be added to concrete to greatly boost its compressive strength and lower its permeability.

However, metakaolin is a pozzolanic clay made from calcined kaolin. Concrete's workability, compressive strength, and longevity can all be enhanced by the addition of metakaolin. Metakaolin can be used to lessen the amount of water needed to make concrete, which in turn makes it denser and more compact. Strength, durability, and workability are just few of the areas where fibers and SCMs combined in concrete can excel. Fibers added to concrete can increase its tensile strength and ductility, while SCMs can boost its compressive strength and longevity. High-performance concrete that is also crack-resistant, long-lasting, and economical can be made with the help of FRC combined with SCMs.Understanding the mechanical and durability features of FRC requires research into the material using silica fume and metakaolin as partial replacement of cement. The research may also shed light on the feasibility of combining FRC with SCMs in building projects. By minimizing the need for cement, the usage of FRC with SCMs can further lessen the environmental toll of making concrete.Increases in compressive strength, tensile strength, and flexural strength are only some of the mechanical qualities of FRC that can be boosted with the addition of silica fume and metakaolin. FRC's resistance to chloride ion penetration, carbonation, and sulfate assault can all be enhanced with the use of SCMs. Toughness and ductility are crucial for structural applications, and they can be improved further by incorporating fibers into FRC.

LITERATURE REVIEW

Uysal, M., Al-mashhadani, M. M., et al, (2018). The study examined the efficiency of geopolymer mortars based on metakaolin and investigated the effects of incorporating colemanite waste and silica fume as partial replacements. Different mix proportions were used, with varying volumes of colemanite waste and silica fume substituting metakaolin. The effectiveness of the mortars was evaluated through tests measuring compressive strength, flexural strength, water absorption, and density. Compressive and flexural strengths were found to be higher in the mix that included colemanite waste and silica fume compared to the control mix. Ten percent colemanite waste and ten percent silica fume produced the maximum compressive strength, a 48% improvement over the control mix. When compared to the control mix, the flexural strength of the mixture with 5% colemanite waste and 10% silica fume was 46% higher. The geopolymer mortars also had less water absorption and density after being mixed with the colemanite waste and silica fume. Increases in colemanite waste and silica fume led to a greater decrease in density and water absorption.

Akcay, B., & Tasdemir, M. A. (2018). The study compared the effectiveness of self-compacting and fiber-reinforced concretes made with silica fume to those made with metakaolin of the same fineness. Compressive strength, flexural strength, slump flow for self-compacting concrete, and toughness for fiber reinforced concrete were tested to determine the efficacy of concretes made with varied concentrations of silica fume and metakaolin. Both self-compacting and fiber-reinforced concretes benefited from silica fume and metakaolin, which increased their compressive and flexural strengths. Slump flow was greater in the self-compacting concrete made with silica fume than in the one made with metakaolin, indicating greater workability.

Venkat, G. N., Chandramouli, K., et al,(2021). In this experiment, M-sand was used as the fine aggregate while silica fume, metakaolin, and GGBS were substituted for part of the cement. Compressive strength, split tensile strength, flexural strength, water absorption, and density were tested on concrete made with a range of mix proportions and variable amounts of each mineral addition. The study discovered that using all three mineral admixtures improved the mechanical properties of the concrete. Out of all of them, silica fume had the most influence on raising the material's compressive strength, while GGBS had the greatest effect on improving the material's split tensile strength and bending strength. A concrete mixture containing 10% silica fume demonstrated the highest compressive strength, whereas a mixture containing 20% GGBS demonstrated the highest split tensile and flexural strengths.

Nežerka, V., Bílý, P., et al, (2019). Interfacial transition zone (ITZ) thickness and strength were analyzed in relation to the addition of silica fume, fly ash, and metakaolin to concrete. The performance of the concrete was measured by measuring the thickness and strength of the ITZ, and different mix proportions were made using different amounts of each mineral addition. A thinner ITZ was seen after silica fume, fly ash, and metakaolin were incorporated into the mix. This is due to the improved packing density and reduced porosity of the concrete, which resulted in a more uniform distribution of cementitious materials throughout the concrete. The reduction in ITZ thickness was more significant with the use of metakaolin compared to silica fume and fly ash.

Ali, A., Aijaz, A., et al, (2018). The research analyzed previous works on the topic of using metakaolin as a partial cement replacement to create nylon fiber reinforced concrete (NFRC). Nylon fiber reinforced concrete (NFRC) is a type of fiber reinforced concrete that makes use of nylon fibers to increase its strength and durability. Metakaolin, a mineral additive, has the potential to replace a portion of cement in concrete mixtures, resulting in improved strength and durability of the material. Reviewing the literature reveals that using metakaolin as a partial substitute for cement can enhance the mechanical properties of normal fiber reinforced concrete (NFRC), including compressive strength, flexural strength, and toughness.

Ding, J. T., & Li, Z. (2002). This research study examines the influence of metakaolin and silica fume on concrete properties. The investigation involved conducting tests on concrete samples with different concentrations of metakaolin and silica fume to evaluate their performance in terms of compressive strength, tensile strength, durability, and workability. The results revealed that both metakaolin and silica fume contributed to increased compressive and tensile strengths of the concrete. Silica fume was observed to enhance the packing density of the concrete by filling voids, while metakaolin acted as a pozzolan, reacting with calcium hydroxide to produce additional calcium silicate hydrates, thereby improving the concrete's performance. By decreasing the concrete's permeability and boosting its resilience to environmental conditions including freeze-thaw cycles and chemical attacks, both mineral admixtures increased its durability.

Singh, L., Kumar, A., et al, (2016). In this study, researchers investigated the potential of utilizing silica fume as a substitute for cement in concrete. Various proportions of silica fume were incorporated into the concrete mix, and tests were conducted to evaluate the impact on compressive strength, split tensile strength, flexural strength, water absorption, and density. The results demonstrated that incorporating silica fume as a partial replacement for cement led to improved mechanical properties of the concrete. Optimal values for compressive strength, split tensile strength, and flexural strength were achieved when replacing 15% of the cement with silica fume.

Scope of the Research

It is possible to conduct a wide variety of studies on fiber reinforced concrete (FRC) using silica fume and metakaolin as partial cement replacements. Here are some possible topics for the study:

Mechanical properties: The modulus of elasticity, flexural strength, and compressive strength of FRC made using silica fume and metakaolin as partial replacements for cement can be studied. Mechanical properties of FRC can be investigated in relation to fiber content and aspect ratio.

Durability properties: Studying the impact of chloride ions, carbonation, and sulfate attack on FRC reinforced with silica fume and metakaolin is possible. FRC's durability can also be studied in relation to fiber composition and aspect ratio.

Workability: The feasibility of using silica fume and metakaolin to partially replace cement in FRC may be assessed by this study. The impact of the materials on the workability of FRC can be determined by measuring the slump, flow, and compacting factor.

Microstructure: Scanning electron microscopy (SEM) and X-ray diffraction (XRD) are useful tools for studying the microstructure of silica fume and metakaolin reinforced FRC. Pore structure, hydration products, and the fiber-matrix contact can all be investigated depending on the types of materials used.

CONCLUSION

The review of utilizing silica fume and metakaolin as partial cement replacements in fiber-reinforced concrete (FRC) highlights their potential in improving the mechanical and durability properties of the material. Through various studies and experiments, it has been demonstrated that incorporating these supplementary cementitious materials (SCMs) in FRC mixes can lead to significant enhancements in performance.

Mechanical properties, including compressive strength, tensile strength, and flexural strength, have shown notable improvements with the addition of silica fume and metakaolin. The pozzolanic reactions between these SCMs and calcium hydroxide contribute to increased cementitious gel formation, resulting in a denser and stronger matrix. This translates into enhanced structural integrity and better crack resistance in FRC.

Durability performance is also positively influenced by the incorporation of silica fume and metakaolin. The reduced porosity of the concrete matrix contributes to enhanced resistance against chloride ion penetration, carbonation, and alkali-silica reaction (ASR). These improvements are critical in extending the service life of FRC structures and minimizing maintenance requirements.

While the benefits of using silica fume and metakaolin in FRC are evident, challenges should be considered. The increased viscosity of fresh concrete, potential impacts on workability, and cost implications associated with these SCMs necessitate careful mix design and optimization strategies. the review demonstrates that silica fume and metakaolin can effectively serve as partial cement replacements in FRC, offering significant improvements in mechanical strength and durability performance. Their utilization contributes to more sustainable and high-performance concrete systems. Further research is recommended to explore optimal dosage, long-term performance, and the influence of other parameters on the behavior of FRC mixes incorporating silica fume and metakaolin.

REFERENCES

[1] V.Ravindar, Rounak Hussain, “Investigation on High Strength Fiber Reinforced Concrete with Silica Fume and Metakaolin as a Partial Replacement of Cement”, International Journal & Magazine of Engineering, Technology, Management and Research, Vol.3, Issue 8, Aug., 2016, PP: 868-872.

[2] Arfath Khan Md, Abdul Wahab, B. Dean Kumar “Fibrous Triple Blended Concrete Composites – Study of Strength Properties”, International Journal of Emerging Technology and Advanced Engineering , Vol. 3, Issue 5, May 2013, PP: 541-546.

[3] P. Muthupriya, K. Subramanian and B. G. Vishnuram, “Strength and Durability Characteristics of High Performance Concrete”, “International Journal of Earth Sciences and Engineering”, Vol. 03, No. 03, June 2010, PP: 416-433.

[4] Vikas Srivastava, Rakesh Kumar, Agarwal V.C, Mehta P. K , “ Effect of Silica fume and Metakaolin combination on concrete”, International Journal of Civil and Structural Engineering, Vol 2, No.3, 2012, PP: 891-889.

[5] Vikas Srivastava, ‘‘Effect of Silica fume and Metakaolin combination on concrete’’, International Journal of Civil and Structural Engineering, Vol. 2, No.3, 2012, PP: 893-900.

[6] V.C Agarwal, ‘‘Metakaolin inclusion: Effect on mechanical properties of concrete’’, International Journal of Civil and Structural Engineering, 2012 Vol. 1, Issue 5, PP: 251-253.

[7] Sudarshan N.M., T. Chandrsekhar Rao, “Mechanical Properties Assessment of Ultra High Performance Fibre Reinforced Concrete (UHPFRC)”, International Journal for Research in Applied Science & Engineering Technology, Volume 3, Issue 6, June 2015, PP: 839-844.

[8] Vinod B. Shikhare, L. G. Kalurkar, “Combine Effect of Metakaolin, Fly Ash and Steel Fiber on Mechanical Properties of High Strength Concrete”, IOSR Journal of Mechanical and Civil Engineering, Volume 7, Issue 1, May 2013, PP: 1-4.

[9] Atul Naik, Sandeep Gaikawad, “Critical Studies on the Influence of Silica Fume and Steel Fiber Enhancing Properties of Concrete”, International Journal for Research in Applied Science & Engineering Technology, Volume 3 Issue 8, July 2015, PP: 552-557.

[10] Ragi S. "A comparative and experimental study on the mechanical properties of various steel and glass fibre reinforced high strength concrete" International research journal of engineering and technology, Volume 02, Issue 04 (2015), PP: 129-133.

[11] Musmar M., "Tensile Strength of Steel Fibre Reinforced Concrete", Contemporary Engineering Sciences, Vol. 6, Issue 5, (2013) PP: 225-237.

[12] Chandramauli K., Srinivasa R. T., Pannirselban N., Seshadri S. G. and Sarvana P. "Strength Properties of glass fibre concrete", International Journal for Research in Applied Science & Engineering Technology, Vol. 5, No. 4, (2010), PP: 1-6.

[13] Pradeepa, "An Experimental Study on Properties of Fibre Reinforced Self Consolidating Concrete" National Conference on Research Advanced in Communication, Computation, Electrical science and structure (NCRACCESS) ISSN 2348-8352 (2015)PP: 38-41.

[14] Khan F. and Ahmad J., "To Study the Properties of Latex Modified Steel Fibre Reinforced Concrete" International Journal of Recent Research in Civil and Mechanical Engineering, Vol. 2, Issue 1, (2015) PP: 261-267.