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A Review On "Experimental Study on the Development of Optimum Concrete Mix Proportion using Ultrafine Materials"

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Abstract- Concrete is the most widely used construction material in infrastructure and building development due to its adaptability, availability, and high compressive strength. However, the increasing demand for high-strength and high-performance concrete has led researchers to focus on improving concrete properties such as workability, early strength gain, durability, and resistance to aggressive environmental conditions. At the same time, cement production contributes significantly to CO_2 emissions, global warming, and depletion of natural resources, which has encouraged the use of supplementary cementitious materials (SCMs) and industrial by-products as partial cement replacements. Among the advanced techniques for improving concrete performance, the utilization of ultrafine materials such as ultrafine fly ash, silica fume, ultrafine GGBS, alccofine, marble powder waste, stone dust, and other microfine powders has gained significant attention due to their filler effect, enhanced particle packing, pozzolanic activity, and microstructure refinement capability. This review paper presents a detailed study of previous experimental investigations on the application of ultrafine materials in concrete for mix optimization. It critically discusses the influence of ultrafine materials on workability, compressive strength, tensile strength, flexural strength, permeability resistance, shrinkage behavior, and microstructural development. Additionally, research gaps are identified related to the lack of standardized mix proportioning guidelines for ultrafine materials, limited combined performance-based optimization studies, insufficient durability assessment under Indian climatic conditions, and lack of field implementation and long-term monitoring. The review concludes that ultrafine materials play a major role in developing optimized sustainable concrete mixtures, but further studies are needed for developing unified design procedures, multi-objective optimization models, and performance-based specifications for large-scale applications.

Keywords: Ultrafine materials, High Performance Concrete (HPC), High Strength Concrete (HSC), Optimum mix proportion, Particle packing, Alccofine, Ultrafine GGBS, Fly ash, Silica fume.

I. INTRODUCTION

Concrete is a fundamental construction material widely used for structural and non-structural applications such as buildings, highways, bridges, dams, tunnels, and industrial structures. Conventional concrete is produced by mixing cement, fine aggregate, coarse aggregate, and water in appropriate proportions. However, modern infrastructure development requires concrete with superior properties such as high compressive strength, improved durability, enhanced workability, reduced permeability, and resistance to aggressive chemical environments. These requirements have led to the development of High Strength Concrete (HSC), High Performance Concrete (HPC), and Ultra High-Performance Concrete (UHPC). The production of cement, which is the primary binding component in concrete, is a major contributor to global CO_2 emissions and energy consumption. It is estimated that manufacturing of one ton of cement releases nearly one ton of CO_2 into the atmosphere. Furthermore, the continuous extraction of natural aggregates and river sand has resulted in serious ecological problems such as riverbed degradation, groundwater depletion, and environmental imbalance. Therefore, the replacement of cement and natural aggregates with industrial by-products, waste materials, and alternative resources has become a key area of research in sustainable construction.

In recent years, ultrafine materials have emerged as promising components in concrete mix design due to their ability to enhance packing density, reduce voids, improve cement hydration reactions, and create a dense microstructure. Ultrafine materials such as ultrafine fly ash, silica fume, ultrafine GGBS, alccofine, stone dust, marble powder waste, and manufactured sand contain particles smaller than cement particles, which helps in pore refinement and strength enhancement. These materials act as fillers and also contribute to pozzolanic reactions, which produce additional calcium silicate hydrate (C-S-H) gel, improving strength and durability. The concept of optimizing concrete mix proportion using ultrafine materials is therefore essential to achieve improved performance, cost-effectiveness, and sustainability. However, achieving optimum concrete mix design is complex due to the combined effects of multiple ultrafine materials, water binder ratio, superplasticizer dosage, aggregate grading, curing conditions, and environmental exposure. Hence, this review paper focuses on previous studies related to ultrafine material incorporation in concrete and highlights the scope for developing an optimum mix proportioning methodology for practical engineering applications.

II. LITERATURE REVIEW

Several researchers have investigated the role of ultrafine materials and supplementary cementitious materials in optimizing concrete mix proportion for achieving higher strength and durability.

Development of High-Performance Concrete Using GGBS and Alccofine (2017) by Syed Nayaz, Arun Kumar, Suresh L, Lohith K.H., and G.M. Jagannatha- Presented an experimental investigation focused on the development of High-Performance Concrete (HPC) by incorporating mineral admixtures such as GGBS and Alccofine 1203 to improve the strength and durability characteristics of concrete. The authors emphasized that high-performance concrete is widely required in modern infrastructure projects due to its superior long-term performance, improved rheological behavior, higher mechanical strength, enhanced durability, and reduced permeability compared to conventional normal strength concrete. In this study, the experimental work was carried out to evaluate key hardened properties such as compressive strength, split tensile strength, and flexural strength for both normal strength and high strength concrete mixes. The authors replaced cement with Alccofine at different percentages, mainly 10% and 15% by weight of cement, and prepared high strength concrete of grade M70 using a constant low water-cement ratio of 0.30, while superplasticizers were added to maintain the required workability. The concrete specimens were cast and cured at atmospheric temperature, and strength tests were conducted at 7 days and 28 days to evaluate early and later age performance. The study highlighted that the inclusion of Alccofine significantly improves early strength development due to its ultrafine particle size and high reactivity, which helps in reducing porosity, enhancing homogeneity, improving the transition zone between aggregate and cement paste, and reducing shrinkage effects in the hydrated cement matrix. The authors also discussed that the design of high-strength concrete depends strongly on maintaining a low water-binder ratio and using high quality cementitious materials with optimum proportions, as recommended by standard guidelines such as ACI 211-4R, DOE method, and IS 10262:2009. Furthermore, the study noted that mineral admixtures such as fly ash, silica fume, GGBS, and Alccofine improve the workability and cohesiveness of fresh concrete, reduce bleeding and segregation, and contribute to producing a denser and more durable concrete structure. The research concluded that producing HPC and high strength concrete with consistent workability and high strength is difficult without chemical admixtures like high-range water reducers, and the experimental findings confirmed that Alccofine-based HPC mixes with low water binder ratio demonstrate better mechanical performance compared to conventional mixes, making them suitable for durable and high-strength infrastructure construction applications.

Experimental Investigation of Properties of Concrete with Partial Replacement of Aggregates with Industrial and Construction Waste (2019) by Achal Jain and Er. Nitin Thakur- Presented an experimental study focused on improving sustainable construction practices by utilizing industrial and demolition wastes as partial replacements for natural aggregates in concrete. The authors highlighted that the continuous depletion of natural resources along with the increasing generation of industrial and construction waste has created an urgent need for recycling waste materials in concrete to reduce environmental pollution and promote sustainable development. In this research, the authors investigated the mechanical performance of concrete mixes in which fine aggregate (sand) was partially replaced with Copper Slag (CS), while coarse aggregate was replaced with Recycled Concrete Aggregate (RCA) obtained from demolished structures. The replacement levels for both materials were varied at 0% (control mix), 10%, 20%, and 30%, and the concrete mixes were designed for M25 grade concrete. The experimental program included testing both fresh and hardened concrete properties, where the slump test was conducted to evaluate workability, while compressive strength and split tensile strength tests were performed after 7 and 28 days of curing. The results indicated that the workability of concrete slightly decreased as the percentage of copper slag increased, but the slump values still remained within acceptable limits for M25 concrete, showing that copper slag can be incorporated without significantly affecting fresh concrete handling. The strength test results revealed that the inclusion of copper slag alone produced significant improvement in compressive and tensile strength due to its dense structure and better particle packing, whereas increasing RCA content showed a reverse trend, leading to reduced strength performance because RCA generally contains adhered mortar and higher porosity. However, the combined or synergistic use of CS and RCA demonstrated that copper slag played a more dominant role in controlling concrete performance, meaning the percentage of copper slag was the more decisive factor compared to RCA in improving compressive and tensile strength. Overall, the authors concluded that copper slag and recycled concrete aggregate can be effectively utilized in structural concrete as sustainable replacement materials for natural sand and coarse aggregates, respectively, offering dual benefits of reducing solid waste disposal problems and environmental pollution while also improving cost efficiency and reducing the carbon footprint of concrete production.

Investigation of Durability of Concrete by Incorporating GGBS and Alccofine (2020) by Srushti P. Rukmangad and Dr. Sudhir P. Patil- Presented an experimental study focused on evaluating the durability performance of concrete by partially replacing cement with industrial by-products such as Ground Granulated Blast Furnace Slag (GGBS) and Alccofine. The authors highlighted that concrete is the most widely used construction material in infrastructure development; however, cement production consumes high energy and releases significant amounts of CO_2, creating major environmental and economic concerns. Therefore, the study emphasized the need for sustainable alternative materials such as pozzolanic industrial wastes and by-products, which can partially replace cement and improve concrete performance. In this research, the authors investigated M30 grade concrete by replacing cement with GGBS at 20%, 40%, and 60%, and with Alccofine at 10%, 12%, and 14%, to analyze the combined effect of these mineral admixtures on strength and durability properties. A series of concrete specimens including cubes and cylinders were cast and tested for key performance parameters such as compressive strength, water permeability, and Rapid Chloride Penetration Test (RCPT), which are essential indicators of durability and long-term resistance against water and chloride ion ingress. The study indicated that incorporating GGBS and Alccofine improves the durability characteristics by refining pore structure, enhancing cementitious reactions, and reducing permeability, which ultimately increases resistance to aggressive environmental conditions such as chloride attack. The authors concluded that the use of GGBS and Alccofine as partial cement replacement materials not only supports sustainable construction by reducing cement consumption and CO_2 emissions but also enhances the durability performance of concrete, making it more suitable for long-lasting infrastructure applications.

Critical Review on Mix Proportioning Stipulations for High Volume Fly Ash Concrete (HVFAC) (2022) by Asif Ahmed Choudhury, Saurav Kar, and Anup Kumar Mondal- Presented a detailed critical review focused on the mix design requirements and proportioning guidelines for High Volume Fly Ash Concrete (HVFAC) as an eco-friendly and cost-efficient alternative to conventional Portland cement concrete. The authors emphasized that modern infrastructure development demands concrete that is not only structurally safe but also environmentally sustainable, economical, and capable of reducing cement consumption to minimize CO_2 emissions. Therefore, HVFAC has gained significant importance as it utilizes a high percentage of fly ash as a partial replacement of cement, thereby reducing dependency on Ordinary Portland Cement and promoting sustainable construction practices. In this review study, the authors systematically analyzed various research papers related to HVFAC and discussed the key mix proportioning parameters that govern its performance, including the importance of maintaining a low water-to-binder ratio (w/b) to achieve desired strength and durability characteristics. The review highlighted that the fineness of fly ash plays a crucial role in improving workability and enhancing pozzolanic reactivity, which contributes to better long-term strength development. The authors also discussed the significant influence of the age factor, noting that HVFAC exhibits slower early-age strength gain compared to OPC concrete but shows substantial improvement in compressive strength as curing time increases due to continuous pozzolanic reactions and gradual formation of cementitious hydration products. Furthermore, the paper explained that mix proportioning is the process of selecting the optimum combination of cement, fly ash, water, coarse aggregate, fine aggregate, supplementary cementitious materials, and chemical admixtures to obtain the required performance at minimum cost, and this process must be carefully modified and optimized based on project requirements. The authors concluded that proper selection of materials, judicious use of mineral and chemical admixtures, and careful control of w/b ratio and curing duration are essential for producing high-performance HVFAC mixes. Overall, the review established that HVFAC is a promising sustainable concrete technology, but its successful implementation depends on well-defined mix design stipulations that ensure both durability and long-term strength performance.

Effect of Ultra-Fine Cement on the Strength and Microstructure of Humic Acid Containing Cemented Soil (2023) by Jing Cao, Fangyi Liu, Zhigang Song, Wenyun Ding, Yongfa Guo, Jianyun Li, and Guoshou Liu- Presented an experimental investigation on the role of Ultra-Fine Cement (UFC) in improving the strength and microstructural properties of humic acid (HA) contaminated cemented soil, particularly focusing on peat soil conditions found in the Dianchi Lake region of Yunnan, China. The authors highlighted that peat soil foundations often create severe construction challenges, and cement mixing stabilization is commonly adopted; however, the presence of humic acid significantly reduces cement reinforcement efficiency. To address this issue, the study prepared simulated peat soil samples by mixing cohesive soil with varying proportions of HA reagent and reinforced them using a composite cement curing agent blended with different percentages of UFC. The research primarily analyzed the relationship between UFC proportion, humic acid content, soaking duration, and strength development of cemented soil. A detailed laboratory experimental program was carried out using Unconfined Compressive Strength (UCS) tests, along with microstructural analysis through Scanning Electron Microscope (SEM) imaging and PCAS microscopic quantitative pore analysis techniques, to evaluate the pore structure modification mechanism. The results clearly demonstrated that increasing the UFC content in the cement curing agent consistently enhanced the strength of HA-containing cemented soil, and UFC significantly reduced the percentage of macropores, resulting in a denser and more compact microstructure. The findings further indicated that the maximum improvement in compressive strength occurred when the UFC proportion increased from 0% to 10%, showing that a relatively small UFC addition yields substantial strength gain. Moreover, the study concluded that the composite curing agent mixed with UFC performed better than ordinary Portland cement (OPC) alone under all soaking conditions, proving UFC's effectiveness in resisting the deteriorating influence of humic acid. Finally, the authors recommended that a UFC proportion of 10% is the most practical and effective dosage for field applications, as it provides improved stabilization performance while also reducing cement consumption, thereby contributing toward sustainable construction practices and lower CO_2 emissions in soil reinforcement engineering.

Mix Proportion Optimization and Early Strength Development in Modified Foam Concrete: An Experimental Study (2023) by Minghui Shi, Guansheng Yin, Pengfei Wei, Jintao Zhang, and Zhaotong Yang- Presented an experimental investigation focused on optimizing the mix proportions of modified foam concrete to improve its hardening quality, mechanical performance, and early-age strength development. The authors primarily studied the influence of a polycarboxylate superplasticizer (PCE) and its combined blending with hydroxypropyl methylcellulose (HPMC) on improving moulding quality and reducing surface pulverisation, which is a major defect in foam concrete. An orthogonal experimental design approach was adopted to identify the optimum parameter combination for four major property indices (PIs), and a multi-index matrix analysis method was applied to comprehensively evaluate various mix parameter combinations and determine the overall optimal performance. The study revealed that incomplete cement hydration is the key reason for surface pulverisation in foam concrete, and this defect can be reduced effectively by incorporating an appropriate dosage of PCE, which improves dispersion and hydration efficiency. However, the authors found that when PCE dosage exceeds 0.1%, foam concrete experiences defoaming and precipitation, resulting in poor stability; this negative effect can be successfully controlled by adding 0.02% to 0.06% HPMC, which improves viscosity and foam stability. The orthogonal analysis further demonstrated that the anti-cracking agent plays a more significant role in influencing strength compared to the thickening agent, while the mechanical performance was found to be most strongly affected by polypropylene (PP) fiber, followed by dispersible latex powder (DLP). Based on the overall evaluation, the research identified the optimal mix combination for improved foam concrete performance as 0.06% HPMC, 0.3% DLP, and 0.5% PP fiber, which provided the best balance of strength, stability, and surface quality. Additionally, the authors examined the role of calcium formate (CaF) in enhancing early compressive strength in foam concrete prepared with the optimum mix proportions, across different density grades. The results confirmed that increasing CaF dosage significantly improves the early compressive strength, mainly by accelerating hydration reactions, although increasing density grade was observed to reduce the 28-day compressive strength, indicating a trade-off between density level and long-term strength development. Overall, this study provides a strong experimental guideline for producing optimized foam concrete with improved early strength, reduced surface pulverization, and enhanced stability, making it highly suitable for lightweight building and insulation applications.

Experimental Investigation on Use of Ultrafine Material in High Strength Concrete (2024) By Weladi Hina Vitthal, Dr. Vinayak Vaidya, and Mr. Bhagwat Patil (2024)- Carried out an experimental study to examine the effectiveness of incorporating ultrafine materials for improving the overall performance of High Strength Concrete (HSC). The study highlights that the utilization of ultrafine materials such as manufactured sand (M-sand), Ground Granulated Blast Furnace Slag (GGBFS), stone dust, and superplasticizer plays a vital role in enhancing both the mechanical strength and durability characteristics of concrete. The authors prepared different concrete mixes by varying the proportions and dosages of these ultrafine materials to evaluate their influence on key engineering properties like compressive strength and flexural strength, along with durability-related performance. Through a detailed laboratory experimental program, the researchers observed that the incorporation of ultrafine particles contributes to improved particle packing, reduction in void content, and better bonding within the cement matrix, resulting in a denser and stronger concrete microstructure. The findings clearly indicated that the addition of ultrafine materials significantly enhances the strength parameters of HSC and also improves durability performance by reducing permeability and increasing resistance against environmental deterioration. Furthermore, the study successfully identified the optimal combinations and dosages of ultrafine materials required to achieve maximum improvement in concrete performance. Overall, this research provides important practical guidelines for engineers and researchers by proving that ultrafine material incorporation is a promising method for producing high-performance, durable, and sustainable high-strength concrete suitable for modern construction applications.

A Study on the Effective Utilization of Ultrafine Fly Ash and Silica Fume Content in High-Performance Concrete Through an Experimental Approach (2024) by Arava Lekhya and N. Senthil Kumar- Investigated the effective replacement of conventional Portland cement with sustainable supplementary cementitious materials (SCMs) such as Ultrafine Fly Ash (UFFA) and Silica Fume (SF) in order to enhance the strength and durability of High-Performance Concrete (HPC) while reducing CO_2 emissions associated with cement production. The authors developed an extensive experimental program in which binary and ternary concrete mixes were prepared by replacing cement with UFFA and SF at replacement levels of 0%, 5%, 10%, and 15%, resulting in a total of 16 different mix combinations. The research was executed in three systematic stages: first, the mechanical performance of HPC mixes was evaluated using compressive strength testing along with Non-Destructive Testing (NDT) at different curing ages; second, durability-related properties such as water absorption, volume of voids, and water permeability were examined to assess long-term resistance against water penetration; and third, advanced microstructural characterization techniques such as XRD (X-ray Diffraction), TGA (Thermogravimetric Analysis), and FTIR (Fourier Transform Infrared Spectroscopy) were conducted at 28 and 90 days to identify the optimum mix composition. The NDT results confirmed that all HPC mixes showed superior quality with ultrasonic pulse velocity values greater than 5 km/s, indicating dense and homogeneous concrete. The findings revealed that the ternary blended mix U10S15 (10% UFFA + 15% SF) achieved the highest compressive strength of 104.28 MPa at 90 days, demonstrating the effectiveness of combined ultrafine materials in producing ultra-high strength concrete. Durability test results further indicated that the U10S15 mix showed excellent resistance to water penetration, with a very low water absorption value of 1.26%, representing nearly 44.9% reduction in absorption with extended curing. Microstructural investigations confirmed that the inclusion of optimized UFFA and SF improved hydration products and created a highly compact microstructure, as reflected through FTIR peak shifts from 950 to 980 cm^{-1}, additional hydration peaks observed in XRD at 28° (2θ), and improved stability in TGA results. Overall, the study concluded that the optimized ternary blend of 10% UFFA and 15% SF significantly improves strength, particle packing, and impermeability, making the concrete highly suitable for critical applications such as water-retaining and hydraulic structures, where high durability and low permeability are essential.

Experimental Study on the Mechanical Behavior of Concrete Incorporating Fly Ash and Marble Powder Waste (2024) by Abdul Ghani, Fasih Ahmed Khan, Sajjad Wali Khan, Inzimam Ul Haq, Dongming Li, Diyar Khan, and Qadir Bux alias Imran Latif Qureshi- Presented a detailed experimental investigation focused on developing an eco-friendly and low-cost green concrete by utilizing fly ash (FA) as a partial replacement of cement and marble powder waste (MPW) as a partial replacement of fine aggregate (sand). The authors emphasized that conventional concrete production heavily depends on cement, which significantly increases construction cost and contributes to global warming due to high CO_2 emissions, and therefore the use of industrial waste materials like FA and MPW offers an effective sustainable solution. In this study, several concrete mix proportions were prepared by varying FA replacement levels from 5% to 25% and MPW replacement levels from 20% to 100%, both individually and in hybrid combinations. The fresh concrete properties such as density, slump/workability, air content, consistency, and setting time were evaluated, while hardened concrete performance was assessed through compressive strength, splitting tensile strength, permeability testing, and microstructural analysis using SEM. The findings showed that replacing sand with MPW significantly improved compressive strength up to an optimum of 40% MPW, beyond which strength gradually reduced due to poor compaction and increased porosity; however, even at 60% MPW, the strength remained higher than the control mix. The study also observed that replacing cement with FA reduced early compressive strength due to slower pozzolanic reaction and reduced lime content, but the reduction remained minor up to 20% FA, indicating FA can be safely incorporated within a limited range. Most importantly, the combined use of FA and MPW produced superior results due to their synergistic pozzolanic and filler effects, and the optimum hybrid mix was identified as F10M40 (10% FA + 40% MPW), which achieved a compressive strength of 4493.46 psi, representing a 16.21% improvement compared to the control specimen. Durability performance was also enhanced, as permeability results confirmed reduced water penetration due to the filler effect of MPW and the additional C-S-H gel formation caused by pozzolanic activity, leading to a denser microstructure. SEM analysis strongly supported these results by revealing reduced voids, improved hydration products, and denser cementitious bonding in optimum blended mixes. The authors concluded that FA and MPW can be confidently used in concrete as sustainable replacement materials without compromising structural performance, and the optimum replacement limits were recommended as up to 10% FA for cement and up to 40% MPW for sand, making this research highly significant for the development of durable, cost-effective, and environmentally sustainable concrete for modern construction applications.

Effect of Ultrafine GGBS on Concrete (2024) by Elavia Rohinton Sam, R. M. Swamy, Dr. Y. S. Patil, Dr. M. S. Kuttimarks, and Jyoti Shivaji Aher- Presented an experimental investigation focusing on the performance improvement of concrete through the incorporation of Ultrafine Ground Granulated Blast Furnace Slag (UGGBS) as a supplementary cementitious material (SCM). The authors highlighted that although conventional GGBS is widely used as a partial cement replacement, limited research has been conducted on the behavior of ultrafine GGBS with very high fineness exceeding 1200 m^2/kg, particularly around 2000 m^2/kg, which can potentially provide superior packing density, enhanced hydration reactions, and improved durability. The main objective of the study was to evaluate the impact of ultrafine GGBS on key concrete properties such as compressive strength, tensile strength, and durability characteristics, while also promoting sustainable construction by reducing the carbon footprint associated with cement production. In this research, concrete mixes of M50 and M60 grades were developed with ultrafine GGBS replacing cement at different replacement levels of 0%, 5%, 10%, and 15%, and an extensive testing program was carried out to evaluate both strength and durability performance. The hardened concrete tests included compressive strength and split tensile strength, while durability evaluation was conducted through Rapid Chloride Penetration Test (RCPT) and water absorption tests, which are critical indicators for permeability resistance and long-term durability. The experimental results demonstrated that the incorporation of ultrafine GGBS significantly influenced concrete performance, and it was observed that a 10% replacement of cement with ultrafine GGBS produced the highest strength improvement, providing superior compressive and tensile strength compared to other replacement ratios. However, in terms of durability performance, the study found that the 15% ultrafine GGBS replacement mix exhibited the best resistance, showing improved chloride penetration resistance and reduced water absorption, indicating a denser and less permeable microstructure. The authors concluded that ultrafine GGBS improves concrete properties due to its high fineness, which enhances particle packing, reduces void content, improves cement paste–aggregate bonding, and increases the formation of hydration products, thereby improving both mechanical strength and durability. Overall, the study suggested that optimized use of ultrafine GGBS can contribute to the development of high-strength, durable, and eco-friendly concrete mixtures, supporting sustainable construction practices by reducing dependence on ordinary Portland cement and minimizing CO_2 emissions.

Optimization Design of Ultra-Fine Supplementary Cementitious Materials Ultra-High Performance Concrete Mix Proportion Based on Orthogonal Experiment (2024) by Binbin Gu, Qinfei Li, Chao Li, Peng Zhao, Pengkun Hou, Heng Chen, Yang Wang, Piqi Zhao, and Xin Cheng- Presented an advanced experimental investigation focused on optimizing the mix proportion of Ultra-High Performance Concrete (UHPC) by incorporating Ultra-Fine Supplementary Cementitious Materials (USCMs) through a systematic orthogonal experimental approach. The authors highlighted that traditional UHPC commonly suffers from major practical drawbacks such as high viscosity, high early-age autogenous shrinkage, and excessive hydration heat release during early stages, which can lead to workability issues and cracking risk. Therefore, with the emergence of ultra-fine grinding technology, USCMs have gained strong attention because they possess higher pozzolanic reactivity and particle packing efficiency compared to conventional supplementary cementitious materials. In this research, the authors investigated the combined effects of three major mix parameters—water–binder ratio, silica fume content, and USCMs content—on the fresh and hardened performance of UHPC, including workability, rheological properties, compressive strength, flexural strength, and early-age autogenous shrinkage behavior. An orthogonal experimental design was adopted, incorporating multiple factors and levels, and the experimental results were analyzed using range analysis, variance analysis, and multi-factor interaction analysis to identify the optimum range and influence degree of each factor. The findings demonstrated that the water–binder ratio had the most significant effect on UHPC performance, strongly influencing fluidity, compressive strength, and autogenous shrinkage, indicating that controlling water binder ratio is the most critical factor in UHPC optimization. The study also revealed that the silica fume content had the strongest influence on flexural strength, showing that silica fume plays a key role in enhancing tensile and flexural behavior through microstructure refinement and improved interfacial bonding. Furthermore, the incorporation of USCMs showed multiple beneficial effects, as compared to the control UHPC mixture, USCMs significantly enhanced the workability and rheological behavior, reduced early-age viscosity, and improved overall flowability. In addition, the study confirmed that USCMs effectively reduced early hydration heat release, which is essential for minimizing thermal cracking risk in mass UHPC applications. Most importantly, the results showed that USCMs could effectively inhibit early-age autogenous shrinkage, thereby improving volumetric stability and reducing cracking susceptibility. Overall, the authors concluded that the optimized use of ultra-fine supplementary cementitious materials provides an effective solution to overcome the traditional drawbacks of UHPC, producing concrete with improved workability, superior strength, reduced hydration heat, and better shrinkage resistance, which contributes significantly toward the practical implementation of high-performance UHPC in advanced structural engineering applications.

Performance Evaluation of High-Performance Concrete Using Ultrafine Mineral Admixture (2024) by Ramdas M. Pise, C.M. Deshmukh, and G.D. Lakade- Presented a detailed experimental investigation focused on evaluating the performance of High-Performance Concrete (HPC) incorporating ultrafine mineral admixtures to achieve improved early-age strength and enhanced durability characteristics. The authors emphasized that HPC is a rapidly evolving research field aimed at producing concrete with compressive strength exceeding 80 MPa, along with superior mechanical and durability properties required for modern infrastructure development. In this study, the researchers primarily examined the early-age compressive strength development of HPC after casting and also evaluated changes in workability, workability retention, compressive strain behavior, flexural performance, resistance against acid attack, early-age shrinkage characteristics, and selected durability properties of optimized concrete mixes. Additionally, the microstructural improvements due to ultrafine mineral admixture incorporation were investigated using Scanning Electron Microscopy (SEM) analysis. The experimental findings indicated that the addition of ultrafine materials significantly enhanced concrete strength and durability when used as a partial cement replacement, due to improved particle packing and increased formation of strength-governing hydration phases, which resulted in a denser hydrated matrix and better aggregate bonding. However, the authors observed that beyond a certain percentage of ultrafine addition, the fresh concrete properties such as workability began to reduce, mainly due to higher surface area and increased water demand. The study further highlighted that the combined use of ultrafine mineral admixture along with fly ash at optimum dosages produced a notable improvement in early-age strength while also moderately enhancing other mechanical parameters such as flexural performance. Moreover, the durability behavior of concrete improved significantly due to pore refinement and microstructural densification, which contributed to higher resistance against chemical attack and better long-term performance. Nevertheless, the authors also reported that a multiple blend system containing selected mineral admixtures increased early-age shrinkage-induced stress levels and brittleness of concrete, indicating that mix optimization is necessary to balance strength gain and cracking risk. Overall, the research concluded that ultrafine mineral admixture is highly effective in producing high-performance concrete with enhanced early-age strength and refined microstructure, and when used in combination with fly ash, it provides an environmentally sustainable and technically efficient approach for developing durable HPC suitable for advanced construction applications in India.

Experimental Study on the Mechanical Performance of Polypropylene Fiber-Reinforced Concrete Incorporating Palm Oil Fuel Ash as Partial Cement Replacement (2025) by Alaa Omar Tanash, Ahmed Mokhtar Albshir Budiea, Mohd Faizal Md Jaafar, Khairunisa Muthusamy, and Fahrizal Zulkarnain- Presented an experimental investigation aimed at developing environmentally sustainable concrete by utilizing Palm Oil Fuel Ash (POFA) as a pozzolanic material and partial cement replacement in polypropylene fiber-reinforced concrete (PFRC). The authors highlighted that the disposal of POFA, a waste by-product from the palm oil industry, causes serious environmental pollution, while cement manufacturing contributes significantly to CO_2 emissions and ecological degradation. Therefore, the study focused on combining POFA with polypropylene fibers to produce greener concrete with improved mechanical performance. In this research, six different concrete mixtures were prepared with varying replacement percentages of cement by POFA, and both fresh and hardened concrete properties were experimentally evaluated. The main tests conducted included workability assessment, water absorption, compressive strength, and splitting tensile strength, which are critical parameters for determining concrete quality and durability. The findings revealed that the inclusion of POFA reduces workability due to its finer particles and higher surface area, which increases water demand. However, at an optimum replacement level of 10% POFA, the concrete demonstrated significant improvement in mechanical strength due to enhanced pozzolanic activity, which promotes the formation of additional cementitious compounds and produces a denser internal microstructure. The results showed that at this optimal level, compressive strength increased by approximately 9.5% compared to the control mix after 28 days of curing, indicating effective strength enhancement without compromising structural performance.

Additionally, the polypropylene fibers contributed to improving tensile resistance and crack control behavior, while POFA helped in refining pore structure and reducing permeability-related defects. The authors emphasized that this study contributes valuable new insights because the application of POFA in polypropylene fiber-reinforced concrete is still an underexplored research area with limited existing literature. Overall, the study concluded that incorporating POFA as a partial cement replacement in PFRC is a promising sustainable approach that not only reduces industrial waste disposal problems but also supports the development of eco-friendly and durable concrete materials suitable for modern construction practices.

Experimental Study on Performance of High-Performance Concrete Based on Different Fine Aggregate Systems (2025) by Xiaojun He, Enjin Zhu, Mingxiang Zhang, Liao Wu, and Peiguo Li- Presented a detailed experimental investigation aimed at evaluating the performance of High-Performance Concrete (HPC) by using different fine aggregate systems, particularly focusing on the replacement of natural river sand with manufactured sand to address the growing scarcity of natural sand resources and the increasing demand for sustainable construction materials. The authors emphasized that river sand is a non-renewable natural resource and its excessive extraction has caused serious ecological and environmental impacts such as riverbed erosion and ecosystem degradation, which has increased the necessity of adopting manufactured sand as an alternative fine aggregate. In this research, the authors developed concrete mixes in which manufactured sand partially substituted river sand at different replacement rates and also examined the condition of full replacement of fine aggregates by manufactured sand. Additionally, the study investigated the influence of key mix design parameters such as water–binder ratio and fly ash content on the workability and mechanical performance of HPC. The experimental results revealed that at manufactured sand replacement levels of 50% and 70%, the workability and strength properties of mixed sand concrete decreased, mainly due to changes in particle shape, surface texture, and gradation characteristics. However, the study also confirmed that reducing the water–binder ratio significantly improved mechanical properties such as compressive strength, flexural tensile strength, splitting tensile strength, and elastic modulus, demonstrating that lower water binder ratio enhances concrete densification and reduces porosity. The authors further reported that increasing fly ash content initially enhanced the strength performance of manufactured sand concrete because of improved particle packing and pozzolanic reaction, but when fly ash content reached 30%, the strength showed a slight decline, although all concrete strength results still met the required design specifications. Microstructural analysis using SEM supported these findings by confirming improvements in internal matrix densification and bonding. Overall, the study concluded that despite slight reductions in workability and mechanical properties at certain replacement ratios, the overall performance of high-performance concrete containing manufactured sand remained satisfactory, and manufactured sand can be effectively adopted as a sustainable and viable full replacement for natural river sand in high-performance concrete production.

Experimental Study and Analysis on Optimized Mix Ratio of Mullite Powder Mortar and Mechanical Properties of Foam Concrete (2026) by Jingshuang Zhang, Ziyang Chen, Yanqing Wu, and Xuhui Xu- Presented a comprehensive experimental investigation aimed at overcoming the major strength limitations of lightweight wall materials by developing an improved mullite powder-based foam concrete with enhanced mechanical performance and durability. The authors focused on optimizing the mix proportion of mullite powder mortar by conducting a three-factor, three-level orthogonal experimental design, in which fly ash, mullite powder, and glass fiber were selected as the primary influencing variables. Using detailed range analysis and variance analysis, the study evaluated performance indicators such as compressive strength, water absorption rate, and softening coefficient to determine the best possible mortar composition. The findings revealed that the optimal mullite mortar mix consisted of 13% fly ash, 15% mullite powder, and 10% glass fiber, which produced a strong and durable mortar with a compressive strength of 29.73 MPa, a low water absorption of 6%, and a high softening coefficient of 0.92, indicating excellent resistance to moisture weakening. After determining the optimized mortar ratio, the authors further investigated the behavior of mullite foam concrete under different foaming agent dosages and two distinct foaming processes, namely constrained foaming and free foaming, by evaluating compressive strength, tensile strength, water absorption, and softening coefficient. The results demonstrated that constrained foaming significantly improved strength and durability compared to the conventional free foaming method, mainly because constrained foaming produced a more stable pore structure with reduced interconnected voids. Among the tested foaming agent dosages, the research identified that 20% foaming agent content provided the most balanced overall performance, achieving compressive strength of 18.09 MPa, split tensile strength of 3.65 MPa, water absorption of 12.09%, and a softening coefficient of 0.82, making it suitable for practical wall material applications. Additionally, microstructural investigations confirmed that hydration products such as C–S–H gel and AFt (ettringite) interacted effectively with mullite particles and aggregates to form a dense internal network structure, reducing porosity and improving load resistance. Overall, the study concluded that mullite powder foam concrete prepared with the optimized mix ratio and constrained foaming method offers a promising solution for producing lightweight yet strong wall materials that satisfy engineering strength requirements while supporting sustainable construction through the utilization of industrial by-products like fly ash.

III. GAP IDENTIFIED

After reviewing the above literature in detail, it is clearly observed that although significant progress has been made in the development of high-performance and high-strength concrete using ultrafine materials, several major research gaps still exist which restrict the formulation of a universally accepted and practically applicable optimum concrete mix proportion. One of the most critical gaps identified is the lack of standardized mix design guidelines specifically addressing ultrafine materials, particularly within the Indian context, as current Indian Standards such as IS 10262 mainly focus on conventional concrete mix proportioning and do not provide clear provisions for ultrafine supplementary cementitious materials like Alccofine, ultrafine GGBS, ultrafine fly ash, silica fume, or ultrafine stone dust. As a result, most researchers have relied on trial-and-error approaches, ACI guidelines, DOE methods, or orthogonal experimental design, which creates inconsistencies in mix proportion results and makes it difficult for field engineers to confidently adopt ultrafine materials for practical construction. Another major gap is the limited availability of studies focusing on the combined use of multiple ultrafine materials, as most of the reviewed investigations concentrate on the effect of a single ultrafine material at a time, such as only Alccofine, only ultrafine GGBS, only silica fume, or only ultrafine fly ash; however, in real construction practice, concrete performance is often improved through blended systems, and very few studies have systematically explored optimum multi-material blending combinations such as ultrafine GGBS with silica fume, fly ash, stone dust, and manufactured sand together, which is essential to establish an optimum performance-based and cost-effective blend ratio. Furthermore, it is evident that most research works focus primarily on achieving higher compressive strength as the main performance indicator, which highlights the gap of inadequate multi-objective optimization, because optimum concrete mix proportion should not be determined only based on strength but must simultaneously satisfy multiple criteria including workability retention, pumpability, flexural and tensile strength, permeability resistance, chloride penetration resistance, sulphate attack resistance, shrinkage control, durability, long-term service life, and economic feasibility, and only a limited number of studies have attempted such multi-performance optimization models. In addition to this, a significant gap exists due to the lack of field-level validation and large-scale practical studies, since most reviewed studies were conducted in controlled laboratory environments using standard cubes and cylinders with ideal curing conditions, whereas actual construction sites experience variations in temperature, humidity, curing practices, workmanship quality, and compaction efficiency, which can greatly influence the real performance of ultrafine material concrete, and therefore field-based investigations are essential for establishing practical reliability. Another crucial research gap is the limited durability assessment under aggressive Indian environmental conditions, because although tests like RCPT, water absorption, and permeability are commonly performed, long-term durability studies under severe exposure conditions such as coastal chloride attack, sulphate-rich soils, acidic industrial environments, polluted urban regions, and extreme seasonal temperature variations typical of Indian climate have not been sufficiently explored, which is necessary for recommending ultrafine concrete in infrastructure such as bridges, coastal structures, sewage treatment plants, and industrial flooring. Moreover, most of the reviewed literature provides minimal attention to shrinkage, creep, and crack propagation behavior, as only a few studies discussed autogenous shrinkage and early-age shrinkage stress, while long-term drying shrinkage, creep deformation, thermal cracking, and microcrack development are generally neglected, despite the fact that ultrafine materials increase surface area, alter hydration kinetics, and may increase brittleness, making crack resistance evaluation essential for structural applications. Additionally, although many researchers have performed SEM analysis to observe microstructure refinement, there is a major research gap related to the absence of microstructure-based mix design validation, because SEM and microstructural investigations are often used only as supporting evidence rather than being directly integrated into the mix design methodology, and limited work has been carried out on correlating pore size distribution, C–S–H gel formation, hydration product quantification, ITZ densification, and microstructural parameters with the selection of optimum ultrafine material dosage. Finally, an important gap identified is that economic analysis and sustainability evaluation are rarely integrated in a detailed quantitative manner, because most studies discuss sustainability benefits only qualitatively without providing comprehensive cost analysis, embodied carbon estimation, life cycle assessment (LCA), cement reduction calculation, and cost-performance ratio evaluation, which is essential for convincing industry stakeholders to adopt ultrafine materials in large-scale construction. Therefore, it can be concluded that although ultrafine materials have proven strong potential for improving concrete strength and durability, future research must focus on developing standardized mix proportioning guidelines, combined ultrafine material optimization, multi-objective performance modeling, real field exposure testing, long-term durability assessment under Indian conditions, shrinkage and creep evaluation, microstructure-driven validation, and integrated sustainability-cost analysis to establish a practically feasible and optimized concrete mix proportion using ultrafine materials.

CONCLUSION

From the detailed review of previous research studies, it is clearly concluded that ultrafine materials play a significant role in improving concrete performance by enhancing particle packing density, reducing void content, improving hydration efficiency, and producing a denser microstructure. Ultrafine materials such as Alccofine, ultrafine GGBS, silica fume, ultrafine fly ash, marble powder waste, and stone dust contribute both physically through filler effect and chemically through pozzolanic reactions, resulting in improved compressive strength, tensile strength, flexural strength, and durability properties. Several studies reported optimum replacement levels of ultrafine materials generally between 10% and 15% for achieving maximum strength improvement, while durability benefits were often observed at slightly higher replacement levels. However, it is also observed that excessive ultrafine material addition reduces workability due to high surface area and increased water demand, which may cause compaction problems and reduction in strength. Although significant progress has been made in this field, major research gaps exist related to lack of standardized mix design guidelines, limited multi-material combination studies, insufficient durability and shrinkage investigation, and lack of field validation. Therefore, future research should focus on developing a comprehensive and performance-based optimum mix design methodology for ultrafine material concrete, integrating strength, durability, microstructure analysis, cost optimization, and sustainability assessment. Such research will help in producing practical and eco-friendly high-performance concrete suitable for modern infrastructure development.

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