

Using Supplementary Cementitious Materials for Sustainable Concrete

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ABSTRACT

The need for infrastructure expansion and the need to preserve the environment, driven by the use of concrete as a building material, are growing daily. Concrete is the second-most-consumed material after water. It is necessary to use alternative, sustainable materials, particularly recycled ones. The construction industry must urgently utilise SCMs (Supplementary Cementitious Materials) or industrial waste as alternatives to cement in concrete manufacturing, as this exacerbates environmental problems and increases cement costs. The development of sustainable, high-performance concrete involves the use of silica fume (SF), metakaolin (MK), and fly ash (FA). The mixture with SF (5–10%), MK (5–15%), and FA (10–30%) maintains workability through optimised water-to-binder ratios and admixtures. Durability assessments, including chloride penetration, sulfate resistance, and water absorption, as well as compressive, flexural, and split tensile strengths at multiple curing ages, are evaluated in this analysis. This research demonstrates how to produce low-carbon, durable, and sustainable concrete suitable for next-generation construction applications. Silica fume (5–10%), metakaolin (5–15%), and fly ash (10–30%) are integrated as partial replacements for cement in a single optimised mix design for a ternary SCM concrete system. The complementary reactivity and particle-packing characteristics of the three SCMs are used simultaneously in this proposed mix to improve the targets' strength, durability, and sustainability. The chloride penetration, sulfate resistance and water absorption for compressive, flexural and split tensile strengths were evaluated at multiple curing ages. The compressive strength and up to 40% reduction in chloride permeability, sulfate-induced expansion compared with the control mix, and the optimised ternary blend achieved about 16% higher 28-day strength, demonstrating low-carbon, durable, and sustainable concrete.

Keywords: Concrete, Supplementary Cementitious Materials (SCMs), Silica Fume (SF), MetaKaolin (MK), Fly Ash (FA), Sustainable Materials

1. Introduction

The most commonly used material in the construction sector is concrete, with annual production close to 10,000 million tonnes. More than 70% of people live in concrete-built buildings, and the rate is improving every year [1]. By 2050, demand for concrete is expected to rise significantly to around 18 billion tonnes due to global population growth [2]. Cement, the primary ingredient in concrete, releases carbon dioxide. Carbon dioxide is a greenhouse gas. The breakdown of calcium carbonate into calcium oxide and carbon dioxide is known as calcination. It is observed that approximately 927 kg of CO₂ are released for every 1000 kg of cement. Globally, the cement industry alone accounts for 7% of CO₂ [3], so reducing these emissions is a major focus of research worldwide. The amount of cement used in concrete is reduced by adding alternatives, such as fly ash and copper. According to research, agricultural wastes such as coconut shells, wood powder, RHA, corn cobs, and sugarcane bagasse can serve as appropriate alternatives to cement. The primary ingredient in concrete is cement, which provides compressive and/or flexural strength. In the building sector, concrete remains the most extensively utilised material [4]. The cement manufacturing is one of the most damaging operations. However, approximately 900 g of carbon dioxide (CO₂) is produced for every 1000 g of cement. So, researchers have been seeking Supplementary Cementitious Materials (SCMs) for many years to partially replace cement in concrete mixtures. The most popular SCMs are Fly Ash (FA) and Blast Furnace Slag (BFS). Many examinations are conducted over 28 days

on concrete mixtures in SCM, but their compressive strength is higher in mixtures without SCM [5].

The urbanisation and infrastructure development of cement and concrete demand is rising as a result of the world's population growth and subsequent requirements. According to the United Nations Environment Programme, 8% of all carbon dioxide (CO₂) emissions are attributed to cement manufacturing, which contributes significantly to global greenhouse gas emissions. In the construction field, concrete is often utilised [6]. In the building sector, it is inexpensive, widely accessible, common, and has a wide range of applications. Over the past few decades, 4.2 billion tonnes of production have grown around the world, and 14 billion cubic metres per year. Therefore, a ton of regular PC (Portland cement) production exhales one ton of CO₂ [7]. CO₂ emissions cause global warming, and remedial activities are necessary to decrease the enormous percentage of greenhouse gas (GHG) emissions that impact the environment. The carbon footprint is to be reduced quickly from the emissions that the construction industry produces. Globally, cement will rise by 4% by 2050 because cement production will rise 12% and CO₂ pollution from the cement industry [8]. Therefore, the cement industry immediately needs additional sustainable materials to reduce carbon emissions and increase energy efficiency in cement production.

The environmental impact at every stage of their lifecycle is reduced by sustainable building materials from recycled resources. This pollution and greenhouse gas emissions are reduced by maximising durability to minimise replacements, utilising recycled or renewable materials, and lowering usage and energy consumption during production. By utilising resources that are sourced locally, sustainable materials also promote health and security because they are non-toxic and frequently support local economies. The portlandite (calcium hydroxide) crystals are additional components formed by chemical reactions of the cement hydration process, which are readily soluble and have certain drawbacks, such as being soluble in water. The sulphates and crystallisation in dihydrate are formed by portlandite's reaction because of expansion and breakage processes. The building construction expansion has raised concerns about sustainable development and brought substantial depletion of natural resources [9]. The non-renewable resource causes major issues because of excessive and inefficient usage. Therefore, the two major issues the construction industry faces are the limited usage of SCMs and the depletion of natural resources. The economy grows for sustainability with the widespread use of sustainable materials, and it becomes essential to assess the building industry's long-term survival [10].

SCMs can help reduce global warming by lowering greenhouse gas emissions and demand for non-renewable natural resources. The effect of SCM adoption on carbon release and the quality of cement composite products are two examples of scientific and sustainable impacts of SCM that have been thoroughly examined [11]. The expenses of implementing SCM, including equipment inputs and labour, are taken into account. SCMs have important social, economic, and environmental implications, making them an essential part of sustainable development in the building sector. Due to the wide variety of sustainable materials currently used in construction and the lack of a robust design for evaluating SCMs, materials that meet SCMs' requirements are being used unintentionally. Therefore, to evaluate the performance of SCMs, a systematic classification and evaluation system is urgently needed. This carefully examines the different types of SCMs used in the construction industry, describing their components, characteristics, engineering capabilities, and environmental impacts. Therefore, it demonstrates specific environmental impacts associated with various SCMs.

Agricultural waste products are used in construction, improving access to affordable construction materials in developing regions and rural areas. It also contributes to effective

agricultural waste management. By transforming agricultural waste into valuable construction materials, we can support rural development and influence urban growth through climate-friendly, low-emission circular value chains. Concrete made with agricultural by-products can achieve performance equal to, or even superior to, that of conventional concrete when properly processed and engineered.

2. Literature Survey

V. S. Ghusale, A. K. Mundhe, V. K. Shirsath, N. B. Vaidya, P. A. Somvanshi and V. D. Wagh, et al.[12] Multi-class programming to evaluate the usage of SCMs as a possible substitute for specific types of cement in the construction of Reinforced Concrete (RC) structures in order to boost their flexural strength. It investigates a wide variety of approaches to improving flexural strength, including the use of recyclable materials, processed steel slag sand, carbon fibre-reinforced polymers (CFRPs), and steel fibre concrete. E. O. Akande *et al.* [13] investigated the mechanical properties of concrete using Polyethylene Terephthalate (PET) and Crushed Coconut Shell (CCS) as substitutes for conventional coarse aggregates to solve the challenge of increasing cost and environmental pollution. Water absorption and slump tests were conducted on fresh concrete to assess workability, while split tensile, flexural and compressive tests were done for hardened concrete, after curing for 7, 14 and 28 days. Results showed that incorporating CCS and PET in concrete improved workability, reduced density, and maintained acceptable mechanical strength.

A. M. Ali, S. S. Ali, A. H. Wanas and M. M. Adnan, et al.[14] GGBS in concrete is added as an additive product that can partially replace cement. The RHA and GGBS are used to improve the qualities of concrete and can be used in the manufacturing of concrete without having a negative effect on the environment. It is therefore a sustainable option that is responsible for the environment. The strength degradation of high-strength concrete may perform differently both during and after fire exposure when compared to conventional-strength concrete. K. N. Le, V. W. Y. Tam, C. N. N. Tran, J. Wang and B. Goggins, et al.[15] Green Star Design maximises Credit 19B.1: Life-cycle affects – Concrete to build in Australia for creating computer-aided method to compute life-cycle GHG exhale for traditional and high-strength concrete. It is the most efficient method for providing a concrete mixture model utilising its life-cycle GHG emissions. The use of coarse and fine aggregates using water-cement proportion for sustainable goals is related to the usage of additional cementitious material to determine concrete strength.

K. A. S. D. Ratnayake and S. M. A. Nanayakkara, et al. [16] found that fly ash affected the self-healing process determined in this experimental study. The water is pumped through artificially created fissures in a specimen while maintaining a steady pressure gradient throughout the specimen for autogenous healing. Along with 0% of fly ash mix, 20%, 30%, and 40% of fly ash percentages were examined. The fly ash percentages used in this investigation had negligible variance across the initial decrease in flow rate; 20% and 30% fly ash combinations exhibit a considerable reduction in sealing time when compared to 0% fly ash, but 40% and higher fly ash percentages show a minor reduction. K. D. Nanayakkara and W. P. S. Dias, et al.[17] introduce Fly ash (FA) is added to OPC (ordinary Portland cement) as additives as pozzolans. The concrete's initial strength is reduced by adding FA to cement as a primary disadvantage. The nano silica (NS) is added to the FA-OPC mixture. The FA substitution ranges from (0 -70%), and NS ranges from (0 to 6%). Tests for workability, compressive strength (3rd, 7th, 28th, & 100th day), sorptivity, and thermogravimetric analysis (TGA) were conducted for cement paste specimens. The finding shows an enhancement in NS and a decrease in workability. M. F. Ahmed, S. H. Rizwan, M. H. Ahmed and M. Batikha, et al.[18] produces cost-effective, environmentally friendly concrete with minimal CO₂ emissions by using

recycled concrete waste (RCW), glass, and ceramic waste from construction demolition waste (CDW). The research shows how to produce green concrete with the benefits of high strength and low cost by including building waste in the concrete mix.

D. N. B. and M. Sood, et al. [19] study evaluates the performance of M-25 concrete mixes by partially replacing conventional coarse aggregates with recycled PCC (Plain Cement Concrete) waste. The research systematically analyses the compressive strength and cost-effectiveness of these innovative mixes. The findings reveal that compared to conventional M-25 concrete mixtures, substituting 50% of coarse aggregates with PCC waste substantially retains its compressive strength while ensuring environmental sustainability and cost effectiveness. S. A. R. S. Hasibuan, H. Prayuda and M. Muhathir, et al.[20] investigated the potential use of banana skin powder (BSP) Barangan Medan as an alternative to cement. The inclusion of BSP Barangan Medan in the concrete mixture, due to its high silica content, is expected to enhance the strength of the concrete by inducing a pozzolanic reaction. The study results showed that compressive strength is increased with 2.5% replacement, but with 5% to 20% substitution, it is reduced. M. A. Kareem and A. A. Hilal, et al.[21] using recycled waste glass (RWG) as coarse aggregate in production of foamed concrete was examined using Image J software. Then, the effect of this addition on the compressive strength of this type of lightweight concrete was investigated. Volumetric percentages of replacement of 20% of glass powder as cement and 25% of fine glass, 25%, 50% and 100% of coarse glass as a replacement of sand were used. 50% of fine and coarse glass instead of sand was used as well as a comparison with conventional foamed concrete was done. All mixes of foamed concrete were prepared with water to cement ratio equals to 0.49 and density of 1200 kg/m³. The experimental results that obtained from the tests, showed a potential of using RWG as powder, fine and coarse glass in the production of foamed concrete.

V. Alkhaldi, A. -H. I. Mourad and M. El Gamal, et al.[22] Sulphur-based concrete is produced by utilising carbide lime waste as aggregate. The mechanical qualities of sulphur concrete proportioned with different kinds of aggregate were accomplished by first characterising the mix components. The mix's characteristics are improved by using fillers, according to the results, and it showed better mechanical qualities. The mix's longevity is demonstrated in this research. S. S. Abdulhussein and A. A. Alfeehan, et al.[23] lightweight concrete was made by reducing coarse aggregate and adding more finite elements to achieve the appropriate strength-to-density ratio. The proportion of steel reinforcement is the same for each slab and its cross-sectional area. The ratio of rib depth, complete portion depth, and the volumetric fraction proportion of iron lathe waste using post-tensioned steel wires as extra tension reinforcement were the characteristics under investigation. A. A. Jawheer, Y. A. Mansoor, A. I. Al-Hadithi and O. A. Hamad, et al.[24] A fuzzy logic model is developed in this research. The waste plastic (polyethene terephthalate, or PET) is used for lab work, obtained from shredded PET bottles. It is used as an aggregate to partially replace natural aggregate in the production of shotcrete concrete. The PET aggregate with percentages of 0%, 1%, and 2.5% by volume of the fine aggregate is replaced with natural aggregate to create shotcrete concrete mixes. The silica fume (SF) and superplasticiser (SP) are utilised for partial replacement by weight. The findings show that the inclusion of waste plastic aggregate has a detrimental effect. The compressive strength of shotcrete concrete findings shows that the inclusion of waste plastic aggregate has a detrimental effect. The projected mechanical qualities (roughly all values) are 45% average inaccuracy for both fresh and hardened concrete. V. J. M. Gulapa et al., [25] Artificial Neural Network model is five various inputs: amount of fine aggregate, coarse aggregate, cement dosage, water-cement ratio, and the waste ceramic. Two derived models are used. The waste ceramic tile without adding any additives was produced with compressive strength and slump workability of concrete. The results show concrete slump and compressive strength tests of this

model. With regression values (0.98007 and 0.99643) and mean square errors (10.218 and 1.4927), there are two (2) generated models that exhibit better accuracy with a maximum error (19.07%) and an average error (2.2%) for slump workability and a maximum error (9.26%) and an average error (1.81%) for compressive strength; all models exhibit exceptional accuracy.

3. Framework for the Use of Supplementary Cementitious Materials for Sustainable Concrete

In this section, a framework using supplementary cementitious materials for sustainable concrete is observed. The raw materials used in this analysis are cement, aggregates, water, silica fume (SF), fly ash (FA), metakaolin (MK), and admixtures. The Materials are tested for chemical composition (XRF), particle size and moisture content, which are used in pre-processing and characterisation. The mixture ratio for binder replacement levels: SF (5–10%), FA (10–30%), MK (5–15%); water-to-binder ratio optimised. The Aggregates and cement dry mixed of SF, FA, and MK added. Then water and admixtures ensure homogeneity in batching and mixing. Test specimens were prepared, compacted, and cured under standard conditions in casting and curing. The Strength tests (compressive, flexural, tensile) and durability tests (chloride, sulfate, permeability) are evaluated in testing. The SEM, XRD, and TGA were used to study hydration and infinite refinement in the microstructural analysis. Then, the results are compared with the control; statistical tools are used for performance validation in data analysis and optimisation. The assessment is based on strength, durability, CO₂ reduction, and cost-effectiveness for performance and sustainability. Optimisation feedback is a mix of proportions adjusted iteratively for the best performance, as in Figure 1.

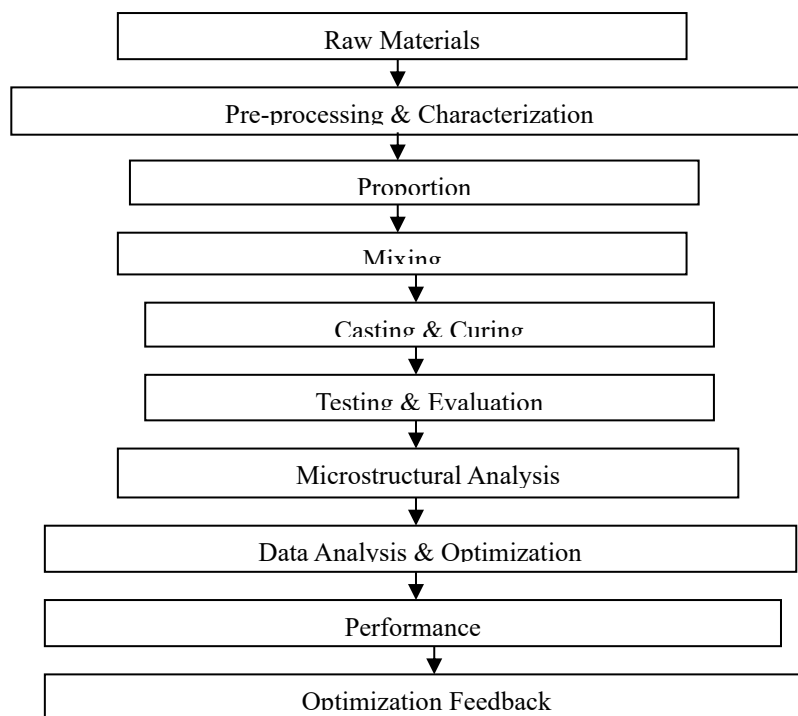


Figure 1: Framework Using Supplementary Cementitious Materials For Sustainable Concrete

In this analysis, M30 grade concrete was designed as the control mix (CM) with a water–binder ratio (0.40), and cement was partially replaced by a ternary blend of Silica Fume (SF), Fly Ash (FA) and metakaolin (MK). The optimised ternary SCM mix (TM) consisted of 8% SF, 20% FA and 10% MK by weight of binder. Standard cube specimens of size (150 mm × 150 mm ×

150 mm) were cast for compressive strength testing. The height of cylinders (150 mm diameter $\times$ 300 mm) was cast for split tensile strength. Prismatic beams of 100 mm $\times$ 100 mm $\times$ 500 mm were cast for flexural strength. The standard deviation is used to compute error margins for each age and each mix, three replicate specimens ($n = 3$) were tested and the average value is reported. All mixes were prepared in a pan mixer, and coarse aggregates and fine aggregates were dry-mixed for 1–2 minutes. Then, cement and SCMs (SF, FA, MK) added and dry-mixed for another 2 minutes to ensure uniform dispersion for fine powders. Approximately 70% of the mixing water, premixed with a polycarboxylate-based superplasticizer, was then added gradually while mixing and remaining water was added to achieve the target slump of 75–100 mm. In the two layers and each layer was compacted on a vibrating table fresh concrete was placed in oiled moulds. Specimens were demoulded after 24 h and then cured in water at 27 ± 2 °C until the time of testing, and compressive strength was measured at 7, 28 and 56 days, whereas tensile and flexural strengths were determined at 28 days. The specific test durability specimens used the same curing regime and were tested at 28, 56 and 90 days.

Compressive Strength(Mpa): Tested at 7, 28, and 56 days (sometimes extended to 90 days for SCM mixes).

Flexural & Tensile Strength: Typically at 28 days.

Durability Tests:

Chloride ion penetration (RCPT): 28 & 56 days.

Water absorption(%) & sorptivity(mm/ $\sqrt{\text{min}}$): 28th day.

Sulfate resistance: monitored up to 90 days.

Microstructural Tests: (SEM, XRD, TGA): Usually done at 28th day(hydration stabilizes).

Silica fume, also known as microsilica, is a finely divided, amorphous silica powder collected as a byproduct during the manufacturing of silicon metal and ferrosilicon alloys. Its extreme fineness and high pozzolanic activity make it a valuable addition to concrete, significantly improving its mechanical strength, durability, and resistance to corrosion by filling voids and reacting with calcium hydroxide to form stronger compounds.

Metakaolin is a pozzolanic supplementary cementitious material added to concrete to enhance mechanical strength, reduce porosity, and improve durability, particularly against aggressive environments. It achieves these benefits by reacting with calcium hydroxide to form additional calcium silicate hydrate (C-S-H) gel, refining the finite structure, and acting as a filler. Metakaolin also contributes to concrete's sustainability by reducing its overall carbon footprint and is used in high-performance, precast, and lightweight concrete applications. Metakaolin increases concrete's mechanical strength, although the optimal replacement rate, often between 5% and 15%, is critical and depends on the specific concrete mix. By reducing porosity and reacting with harmful substances, metakaolin improves durability by decreasing water absorption, gas permeability, and resistance to chloride ingress and other forms of chemical attack. Using metakaolin as a partial replacement for Portland cement helps lower the overall carbon emissions of concrete production, as it requires less energy to produce than cement.

4. Result Analysis

In this section, the result analysis of using supplementary cementitious materials for sustainable concrete is observed. In Table 1, the proposed system is compared with the existing system in terms of compressive strength, durability and sustainability.

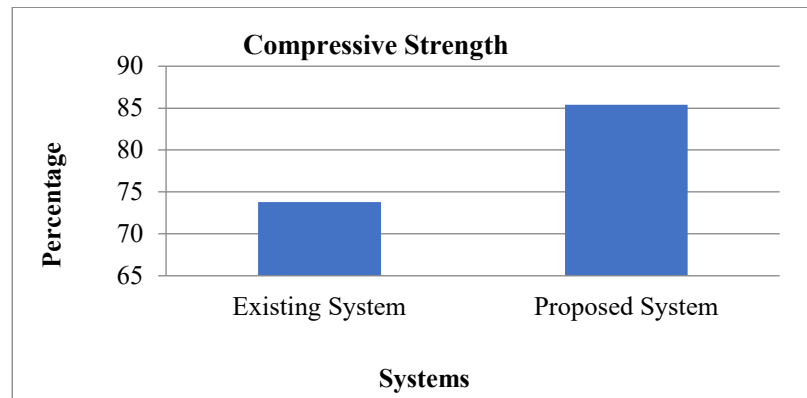


Figure 2: Compressive Strength Comparison Graph

Table 1: Performance Comparison

The

Parameters	Existing System	Proposed System
Compressive strength (%)	73.8	85.4
Durability (%)	89.5	94.5
Sustainability (%)	88.4	91.7

compressive strength (Mpa) is compared between existing system and proposed system in figure 2. The inclusion of silica fume and metakaolin enhances early-age strength through rapid pozzolanic reactions and micro-filler effects. The fly ash contributes to long-term strength gain. The existing system is compared with proposed system in figure 3. Silica fume and metakaolin limit chloride ingress and carbonation, while fly ash provides resistance to sulfate attack through secondary hydration products. The ternary blend significantly improves durability by refining the infinite structure and reducing permeability as per the Figure 3.

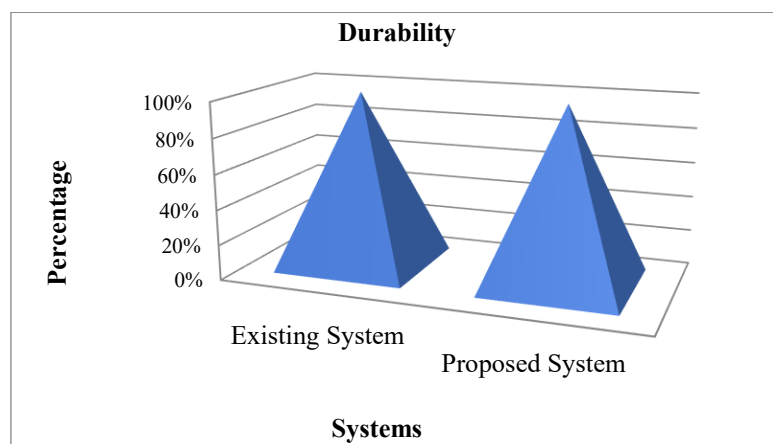


Figure 3: Durability Comparison Graph

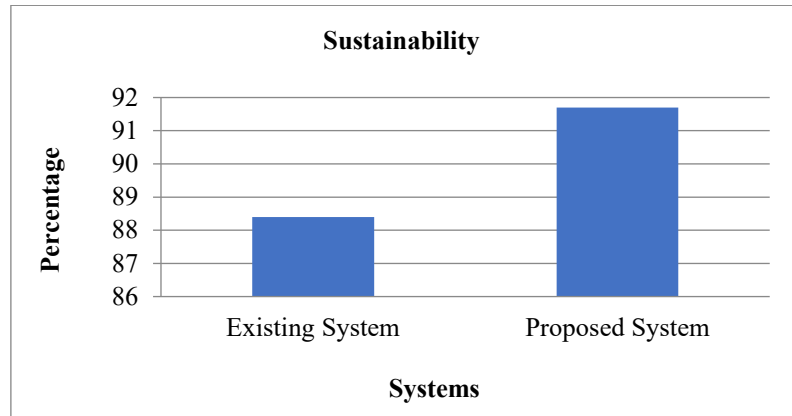


Figure 4: Resistance Comparison Graph

The sustainability is compared between existing system and proposed system in figure 4. Sustainability is achieved by partially replacing cement with industrial byproducts, thereby reducing clinker demand and embodied carbon.

The table 2, shows graphical or tabulated data with error margins for compressive, tensile, and durability tests for 7, 28 and 56 days.

Table 2: Performance Comparison

Property	Age (days)	Control Mix (CM)	Ternary SCM Mix (TM)	Improvement (%)
Compressive strength (MPa)	7	32.5±1.2	37.8±1.0	16.3
Compressive strength (MPa)	28	46.9±1.5	54.4±1.3	16.0
Compressive strength (MPa)	56	50.8±1.4	59.2±1.2	16.5
Split tensile strength (MPa)	28	3.70±0.10	4.25±0.12	14.9
Flexural strength (MPa)	28	5.15±0.18	5.95±0.17	15.5
RCPT charge passed (Coulombs)	28	2100±90	1350±75	-35.7
RCPT charge passed (Coulombs)	56	1850±80	1100±65	-40.5
Water absorption (%)	28	4.20±0.15	3.35±0.12	-20.2
Sorptivity (mm/√min)	28	0.195±0.008	0.150±0.006	-23.1
Length change in 5% Na ₂ SO ₄ (%)	90	0.075±0.004	0.045±0.003	-40.0

The synergistic pozzolanic and filler effects of silica fume, metakaolin and fly ash attributes for ternary SCM mix compared with the control and typical single-SCM systems. At early ages, calcium hydroxide rapidly reacts silica fume with its extremely fine particle size and high amorphous silica content that fills micro-voids, thereby densifying the interfacial transition zone. The calcium silicate hydrate (C–S–H) and calcium aluminate silicate hydrate (C–A–S–H) gels provide highly reactive aluminosilicate phases of metakaolin for further refining the pore structure. The long-term strength and durability through secondary hydration and refinement of capillary pores contributes fly ash at time of slower reaction. These SCMs consume a larger fraction of portlandite, reduce connectivity of pores, and enhance packing density of the binder matrix used together in optimized proportions. Therefore, it shows improvement in compressive strength, tensile strength and durability.

5. Conclusion

This research describes that the blended use of silica fume, metakaolin, and fly ash in concrete not only enhances strength and durability but also contributes to sustainable construction by reducing the dependence on ordinary Portland cement. The resistance to aggressive environments is improved, and long-term performance is enhanced by the synergistic action of these SCMs, which refine the finite structure. The optimised ternary/quaternary blends achieved higher compressive strength, durability, and sustainability than the existing system. This system significantly reduces carbon emissions and promotes circular-economy practices by incorporating industrial and agricultural by-products. The integration of SF, MK, and FA is a viable, eco-efficient strategy for producing sustainable, high-performance concrete. The optimised ternary mix (8% SF + 20% FA + 10% MK) achieves 16% higher compressive strength than the control mix at 7, 28, and 56 days, and compressive strength increases from 46.9 MPa (CM) to 54.4 MPa (TM) at 28 days. The 28-day split tensile and flexural strengths of the ternary SCM concrete were improved by approximately 15% compared with the control mix. It indicates a more efficient stress transfer and a denser interfacial transition zone. Durability indicators demonstrated significant improvements: RCPT charge reduced by 36–41%, water absorption by about 20%, and sorptivity by about 23%. The sulfate-induced expansion at 90 days was around 40% lower than that of the control mix. The strength and durability are enhanced by reducing cement clinker content, thereby differentiating it from conventional single-SCM or purely aggregate-based sustainability approaches by integrating optimisation of an SF–MK–FA ternary binder.

Conflict of Interest: The authors declare that they have no conflicts of interest.

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