A Literature Study on Sustainable Blended Concrete incorporating Wastes

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ABSTRACT:

Rising construction costs in today's market are largely driven by the high consumption of cement, a material whose production is both energy-intensive and a major contributor to greenhouse gas emissions. In response, the construction industry is increasingly turning to sustainable alternatives, notably Supplementary Cementitious Materials (SCMs), to partially replace Ordinary Portland Cement (OPC). This literature-based study examines the performance of binary, ternary, and quaternary blended concretes incorporating industrial and agricultural waste by-products such as Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Silica Fume (SF), Metakaolin (MK), Rice Husk Ash (RHA), and Vitrified Tiles Powder (VTP). The study emphasizes concrete durability—its ability to resist environmental, chemical, and physical degradation over time—alongside mechanical performance. Results across various mix designs and strength grades indicate that SCM incorporation enhances key durability parameters, including reduced water permeability, chloride ion penetration, and carbonation depth, as well as improved pore structure. Mechanical properties such as compressive, flexural, and split tensile strengths also showed notable improvements, especially in well-optimized quaternary blends. The effectiveness of each SCM, through mechanisms like pozzolanic reactivity, filler effect, and microstructural densification, underscores their potential to significantly reduce OPC usage while ensuring durable and high-performance concrete in modern construction.

Keywords:*Durability, Supplementary Cementitious Materials, Quaternary Concrete, Sustainable Construction, Microstructure enhancement*

1. INTRODUCTION:

Blended concrete is a type of concrete that incorporates supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, or natural pozzolans along with ordinary Portland cement (OPC). The growing necessity of blended concrete in modern construction stems from its numerous advantages in terms of sustainability, performance, cost-efficiency, and durability. As the construction industry faces increasing pressure to reduce its environmental footprint, blended concrete offers a viable solution that supports both structural integrity and ecological responsibility.

One of the primary reasons for using blended concrete is its environmental benefit. The production of Portland cement is highly energy-intensive and contributes significantly to global carbon dioxide emissions. By partially replacing OPC with industrial byproducts like fly ash or slag, the overall carbon footprint of concrete is significantly reduced. This practice not only conserves natural resources used in cement production but also helps in managing industrial waste that would otherwise occupy landfills or contribute to environmental pollution. Thus, blended concrete plays a vital role in sustainable construction and supports green building initiatives.

In addition to environmental benefits, blended concrete improves the long-term performance and durability of structures. SCMs react with calcium hydroxide in the cement paste to form additional calcium silicate hydrate (C-S-H), the compound responsible for strength and binding in concrete. This reaction leads to a denser and more refined microstructure, which reduces the permeability of the concrete. As a result, blended concrete is more resistant to chemical attacks such as sulfate and chloride intrusion, which are common causes of deterioration in concrete structures. It also reduces the risk of alkali-silica reaction (ASR), a phenomenon that can lead to cracking and expansion in traditional concrete.Blended concrete often exhibits improved workability and finishability, especially in hot or dry climates where conventional concrete may set too quickly. Some SCMs, like fly ash, provide a smoother texture and better cohesion, making the concrete easier to place and compact. While blended concrete may gain strength at a slower rate initially compared to OPC, it generally achieves equal or even greater strength over time. This makes it particularly suitable for large-scale infrastructure projects and structures requiring long service lives.

Cost-effectiveness is another compelling reason for the growing use of blended concrete. SCMs are typically less expensive than Portland cement, reducing the overall cost of materials. Moreover, the enhanced durability and lower maintenance requirements of blended concrete result in reduced life-cycle costs for structures. In the long run, this contributes to economic savings for builders, property owners, and governments.Finally, the use of blended concrete is increasingly mandated or encouraged by building codes and environmental certification programs such as LEED. These standards aim to promote sustainable practices in the construction industry and often reward the use of low-impact materials like blended concrete.

In conclusion, blended concrete is not just an alternative to traditional concrete but a necessary advancement in response to modern construction demands. Its environmental benefits, improved performance, cost efficiency, and alignment with sustainability standards make it an essential material for future-ready infrastructure.

2. Literature Review:

2.1 Utilization of Ground Granulated Blast furnace Slag (GGBS), Silica Fume (SF) and Fly Ash (FA) in concrete:

ShreekanthBirgonda et. al., (2023) has studied the quaternary blended self-compacting concrete (QBSCC) mixes incorporating induction furnace slag (IFS) and crushed stone aggregate. 0.4. The quaternary blended mixes are created by combining OPC, class F Fly Ash (FA), Silica Fume (SF) and Ground Granulated Blast Furnace Slag (GGBFS). The replacement ranges for SF are set between 2.5% and 7.5% in increments of 2.5%, for FA between 10% and 20% in increments of 5%, and GGBFS between 30% and 50% in increments of 10%. A total of 918 cubes are casted and tested for compressive strength, flexural strength, split tensile strength, Elastic Modulus, Pull off strength and Shear strength. Fresh properties like Slump flow, V funnel test, J-Ring test, L- Box test are done. OPC57.5% GGBS30% FA10% SF2.5% is obtained to be optimum mix among others. Superior compressive strength of 46.80MPa with IFS aggregate which is 6% more than control mix. Split tensile strength of 4.12 MPa increased by 6% at 56 days. Flexural strength of 7.25MPa increased by 9% at 5 days. Elastic modulus of 35.2 GPa obtained at 56 days. Pull out bond strength of 15.9 MPa obtained at 56 days. Slump flow obtained: 660–690 mm. T50 time obtained is 3.2-4.2 sec. V funnel obtained as 7.6- 10.9. L-Box test is obtained as 0.85-0.91. J- ring result obtained as 630-665 mm. These results indicate that the optimized QBSCC mixes exhibit good workability, strength, and durability while incorporating supplementary cementitious materials (SCMs).

Ashok D. Chavan et al., (2024) conducted a study on the strength and durability of M70 grade quaternary blended concrete incorporating supplementary cementitious materials (SCMs) such as fly ash (FA), ground granulated blast furnace slag (GGBS), and micro silica (SF). The concrete mixes were evaluated for compressive strength, Rapid Chloride Penetration Test (RCPT), Rapid Chloride Migration Test (RCMT), and electrical resistivity. The researchers identified an optimum blend consisting of 25% GGBS, 15% FA, and 10% SF as partial replacements for Ordinary Portland Cement (OPC). This mix achieved a compressive strength of 76 MPa after 28 days of curing, marking an 8.5% improvement compared to the control mix. Durability performance also significantly improved, with only 510 coulombs passed in RCPT at 28 days, indicating very low chloride ion permeability. To enhance workability and retention, Sika Viscocrete 5210N was used at 1.5% of the total binder weight. The study demonstrates that optimized quaternary blends can effectively improve both mechanical and durability properties in high-performance concrete applications.

Naitik Patel et al., (2016) studied the compressive and flexural strength of M40 grade quaternary blended concrete by replacing 30% of Ordinary Portland Cement (OPC) with supplementary cementitious materials (SCMs), namely fly ash, silica fume, and ground granulated blast-furnace slag (GGBS). The optimal blend was identified as 15% fly ash, 7.5% silica fume, and 7.5% GGBS, with a cement content of 402 kg/m^3 and a water-to-binder ratio of 0.34. The results demonstrated a 25% increase in compressive strength at 28 days, along with notable improvements in flexural strength at 7, 28, and 56 days. These findings highlight the effectiveness of quaternary blended concrete in enhancing mechanical performance while reducing cement usage. The study underscores the potential of such blends as sustainable, eco-friendly alternatives in modern construction, contributing to lower environmental impact without compromising structural integrity.

Hemanth S. Chore et al. (2020) investigated the strength characterization of M40 grade concrete incorporating industrial waste materials as partial replacements for cement, with a focus on applications in rigid pavements. The study utilized Fly Ash (FA), Silica Fume (SF), and Ground Granulated Blast Furnace Slag (GGBS) as supplementary cementitious materials. An optimal mix was identified with 90% Ordinary Portland Cement (OPC) and equal proportions of 3.33% each of SF, GGBS, and FA. Concrete specimens were tested for compressive strength, flexural strength, and split tensile strength. After 28 days of curing, the compressive strength achieved was 54.15 MPa, reflecting a slight increase of 0.27% compared to the control mix. A flexural strength of 10 MPa was recorded with a 10% total replacement (3.33% of each SCM), while the split tensile strength for the same mix reached 4.8 MPa. The results indicate that even low-percentage replacements using industrial waste can yield concrete with mechanical properties suitable for rigid pavement applications, offering both performance and environmental benefits.

Ashika et al. (2017) investigated the effects of quaternary blending of supplementary cementitious materials (SCMs) in the development of self-compacting concrete (SCC), focusing on high-performance M60 and M80 grade mixes. The study utilized ground granulated blast furnace slag (GGBS), silica fume (SF), and fly ash (FA) as partial replacements for Ordinary Portland Cement (OPC), with replacement levels ranging from 30% to 50%. Four quaternary blended concrete (QBC) mixes were designed and evaluated for both fresh and hardened properties. Fresh properties were assessed using slump flow, U-box, and T50 flow time tests. Slump flow values ranged from 652 mm to 710 mm for M60 grade and 670 mm to 720 mm for M80 grade, all within the acceptable limits for SCC. T50 flow times were between 2.4–2.45 seconds for M60 and 2.5–2.7 seconds for M80, complying with the recommended range of 2–5 seconds. Hardened concrete tests included water permeability, carbonation depth, and mercury intrusion porosity at 7, 28, 56, and 91 days. The QBC mixes showed improved water permeability results compared to the control, with M60 concrete ranging from 3.8 to 4.2 mm (versus 5 mm for control) and M80 ranging from 2.8 to 3.1 mm (versus 4 mm for control) after 7 days. Carbonation depth was recorded as nil for both grades, indicating excellent resistance. Mercury intrusion porosimetry revealed a total porosity of 5.768%, indicating low permeability and dense microstructure. The study confirms the suitability of quaternary blended SCC for high-strength, durable applications, and suggests further research into additional durability and hardened concrete properties.

Sridevi et al. (2021) investigated the permeability characteristics of Quaternary Blended Bacterial Self-Compacting Concrete (QBBSCC) incorporating *Bacillus subtilis* (MCC 2183). A single quaternary mix was designed with 40% cement, 10% micro silica, 25% fly ash, and 25% ground granulated blast furnace slag (GGBFS), and was assessed for microstructure, water permeability, and rapid chloride penetration. The study explores the growing interest in bacterial concrete, where bacteria precipitate calcite through metabolic activity, effectively sealing micro-cracks and pores, thereby enhancing concrete durability. The use of *Bacillus subtilis* in the SCC mix demonstrated notable improvements in permeability resistance. Compared to quaternary blended self-compacting concrete (QBSCC) without bacteria, QBBSCC showed a 35.97% reduction in water permeability at a water-to-binder (w/b) ratio of 0.3, and a 23.3% reduction at a w/b ratio of 0.4. Similarly, RCPT results indicated a 45.05% decrease in chloride ion permeability at w/b 0.3 and a 30.52% reduction at w/b 0.4. The significant reduction in permeability was attributed to the combined effect of bacterial calcite precipitation and the dense matrix achieved through the use of supplementary cementitious materials. Overall, the study confirms that integrating bacteria into quaternary blended SCC can significantly enhance its durability by reducing pore connectivity and improving impermeability.

Aamar Danish et al. (2024) conducted a performance assessment of quaternary-blended geopolymers incorporating materials such as waste marble powder, fly ash, ground granulated blast furnace slag (GGBS), silica fume, metakaolin, and river aggregate, under varying curing temperatures. The specimens were tested for compressive strength, flexural strength, durability (porosity, water absorption, acid resistance), thermal stability, and cost analysis. The optimal mix ratio of GGBS: FA: SF: MK was found to be 12:4:1:1. This mix achieved the highest compressive strength at both curing temperatures: 63.25 MPa at 50°C and 83.23 MPa at 70°C. The flexural strength was 8.51 MPa at 50°C and 11.03 MPa at 70°C. Durability tests revealed the lowest apparent porosity of 4.72% at 70°C, water absorption of just 2.84%, and sorptivity of 0.28 kg/m². Thermal stability was also commendable, with a mass loss of only 2.67% at 500°C. In terms of acid resistance, the mix with a ratio of 1:1:0.62 demonstrated superior performance, especially under exposure to hydrochloric acid (HCl) and sulfuric acid (H_2SO_4), showing lower mass and compressive strength loss. In contrast, the mix ratio of 1:1.83:0.62 performed poorly due to the high calcium content in waste marble powder (WMP), which reacted with acids to form expansive compounds.

Niragi Dave et al. (2017) investigated the compressive, flexural, and tensile strengths of quaternary blended concrete with reduced cement content, incorporating supplementary cementitious materials such as fly ash (FA), ground granulated blast furnace slag (GGBS), metakaolin (MK), and silica fume (SF). These materials were blended in predetermined proportions, replacing 30-50% of Ordinary Portland Cement (OPC) by weight. The water-to-binder ratio and total cementitious content for the M40 grade quaternary mix were kept constant at 0.40 and 440 kg/m³ for all mixes. The results were compared with the control concrete made from 100% OPC. The quaternary blended concrete exhibited significant improvements, with compressive strength, flexural strength, and tensile strength showing increases of 25%, 10%, and 11.2%, respectively, compared to the control mix. The maximum ultrasonic pulse velocity (UPV) recorded was 6172 m/s at ages ranging from 28 to 365 days. Furthermore, chloride permeability was reduced by 78.2%, and the maximum sulfate expansion decreased from 0.48% in plain concrete at 365 days to 0.03% in the quaternary blend, demonstrating enhanced durability.

2.2Utilization of Silica Fume (SF) and Fly Ash (FA) along with other material in concrete:

Saresh Arya et al. (2017) investigated the strength characteristics of multi-blended cement concrete by partially replacing cement with silica fume, rice husk ash, and fly ash. Three ternary mixes were prepared: 20% fly ash and 10% silica fume (10SF10RHA), 30% fly ash and 10% silica fume (20FA10SF), and 30% fly ash with 10% rice husk ash (20FA10RHA), as well as a quaternary mix (20FA10SF10RHA). These mixes were tested for compressive strength, flexural strength, and split tensile strength. The results showed that the 20FA10SF mix exhibited the highest compressive strength of 36.4 MPa at 28 days, surpassing the other blends, while the quaternary blend (QBC) achieved 31.1 MPa, which was lower than the control mix. For split tensile strength, the ternary mixes yielded 4.24 MPa, with the quaternary mix showing 3.25 MPa at 28 days. The flexural strength for the ternary mixes was 4.12 MPa, while the quaternary mix reached 3.18 MPa. In all strength tests, the quaternary blend showed lower results compared to the control mix. However, the ternary mix of 20FA10SF showed a 3.6% increase in compressive strength, an 18.7% increase in split tensile strength, and a 25.22% improvement in flexural strength compared to the control mix.

Rakesh Choudhary et al. (2021) evaluated the durability performance of self-compacting high-strength concrete (SCHSC) using quaternary blends that incorporated waste marble slurry (WMS), fly ash (FA), and silica fume (SF). A total of 16 mix designs were created, with one control mix, where cement content was replaced with WMS (0-15%), FA (10-20%), and SF (5%). Various durability tests were conducted on the quaternary blended concrete (QBC), including water permeability, chloride penetration, carbonation, corrosion resistance, shrinkage, X-ray diffraction analysis, and compressive strength tests. The study identified an optimal mix of 10% WMS, 15% FA, and 5% SF, which showed satisfactory results across all tests. The best outcomes in carbonation, corrosion resistance, and drying shrinkage were achieved with the FA15 mix. The optimum blend (SF5, FA15, WMS10) resulted in an improved compressive strength of 62.56 MPa, which was 7 MPa higher than the control mix. The mix with 35% fly ash (FA35) demonstrated the lowest water permeability value of 11 mm, showing an 84.21% reduction in water penetration depth compared to the control mix. This decrease in permeability was attributed to the resistance developed by FA. Additionally, the FA35 mix exhibited the lowest chloride penetration depth, with a reduction of 72.37% compared to the reference mix (SF5), highlighting the enhanced chloride penetration resistance due to the pore refinement effect of fly ash.

The highest carbonation depth was observed in the mix with the combined highest substitution levels of waste marble slurry (WMS) and fly ash (FA), with the FA35WMS20 mix showing a carbonation depth of 17 mm. In contrast, the self-compacting concrete (SCC) mix with 15% FA and 10% WMS (FA15WMS10) exhibited a carbonation depth of only 1 mm after 90 days of exposure. Although the carbonation depth for FA15WMS10 was slightly higher than the Ref-2(SF5) mix, the difference was negligible. The combined use of WMS and FA in the quaternary SCC mixes provided better resistance against corrosion. All quaternary mixes, except FA35WMS20, showed higher half-cell potential values compared to the Ref-2(SF5) mix. However, the FA35WMS20 mix exhibited more negative values, indicating a 90% probability of corrosion after 180 days of exposure. Conversely, all other quaternary mixes, including FA15WMS10, demonstrated a 90% probability of no corrosion after 90 days. The FA15WMS10 mix also showed the lowest drying shrinkage at 180 days, which was 27.78% lower than the Ref-1 (OPC) mix. This reduction in shrinkage was attributed to the 25% reduction in cement content and the optimal particle packing in the mix. The reduced permeable voids helped prevent water loss, leading to lower drying shrinkage. X-ray diffraction (XRD) analysis of the FA15WMS10 mix revealed a combination of physical and chemical effects from WMS and FA, with peaks for calcite, dolomite, and calcium silicate hydrate (CASH) phases, indicating that both materials contributed to the enhanced strength of the mix.

Praseeda et al. (2021) investigated the development and performance of quaternary blended concrete incorporating industrial wastes such as vitrified tiles powder, silica fume, and fly ash. The study identified the optimal mix as 60% cement, 25% vitrified tiles powder, 7% silica fume, and 8% fly ash, which demonstrated improved strength and durability properties. Sixteen different mix designs were developed and evaluated through a variety of tests, including compressive strength, split tensile strength, flexural strength, ultrasonic pulse velocity, X-ray diffraction (XRD), scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), and thermogravimetric analysis (TGA). The results showed that the optimum mix achieved a compressive strength of 39 MPa, surpassing the target mean strength for M30 grade concrete. Notably, the strength of the quaternary blend improved significantly over time, with compressive strength increasing by 19% at 56 days and 15% at 91 days compared to the reference mix. Similarly, the split tensile strength and flexural strength of the optimum mix showed substantial gains. At 28 days, the split tensile strength was 6% higher, and at 91 days, it was 12% higher than that of the conventional mix. Flexural strength also improved, with the optimum mix outperforming the reference mix by 10% at 28 days and maintaining superior values at 56 and 91 days. These enhancements were attributed to the densification of the microstructure, as observed in SEM images, which revealed closely packed particles and reduced porosity in the matrix.

The inclusion of silica fume and vitrified tiles powder played a key role in densifying the interfacial transition zone (ITZ), thereby improving the mechanical properties of the concrete. X-ray diffraction (XRD) analysis supported this observation, revealing a reduced content of portlandite ($Ca(OH)_2$) in the optimum mix compared to the reference mix. This reduction signifies enhanced pozzolanic activity, where the supplementary materials reacted with calcium hydroxide to form additional calcium silicate hydrate (C-S-H) gel, which is essential for strength development. Thermogravimetric analysis (TGA) further confirmed these findings, showing minimal weight loss and decomposition of hydration products in the optimum mix, suggesting improved thermal stability. The decomposition of crystalline phases at higher temperatures was also lower, indicating better thermal performance. Ultrasonic pulse velocity (UPV) tests demonstrated that the optimum mix had excellent quality, with UPV values exceeding 5000 m/s, indicating a dense and well-packed matrix. A strong correlation between UPV and compressive strength was also observed, reinforcing the superior quality of the mix. Energy dispersive X-ray spectroscopy (EDS) analysis provided additional insights into the elemental composition, showing higher peaks for calcium and silica in the optimum mix, which further indicated increased C-S-H gel formation and a refined pore structure.

Rakesh et al. (2020) explored the effects of silica fume (SF), marble slurry powder (MSP), and fly ash (FA) on the mechanical properties and abrasion resistance of high-strength self-consolidating concrete (HSSCC). In the study, Ordinary Portland Cement (OPC) was replaced with SF, MSP, and FA in various proportions, resulting in a total of 16 mixes. A control mix containing only OPC as a binder was prepared, followed by a secondary control mix where 5% of the OPC was replaced with SF (labeled as S5F0M0), and SF was included in all subsequent mixes. OPC was then substituted with FA and MSP in ratios of 15%, 25%, and 35%, and 10%, 20%, and 30%, respectively. The optimal mix was found to be 5% SF, 10% MSP, and 15% FA. The mixes were tested for various mechanical properties, including compressive strength, split tensile strength, flexural tensile strength, pull-off strength, ultrasonic pulse velocity (UPV), dynamic modulus of elasticity (DME), abrasion resistance, and microstructural properties. The self-consolidating concrete mixes were designed to achieve a target slump flow diameter of 725 ± 25 mm, with most mixes meeting the acceptable range of 705 to 745 mm. The highest compressive strength (62.56 MPa) was achieved by the S5F15M10 mix at 28 days, along with the highest flexural strength (7.25 MPa) and split tensile strength (6.028 MPa). The pull-off strength for this mix was 4.18 MPa, and the UPV values ranged from 5034 to 5405 m/s, indicating excellent concrete quality (UPV > 4500 m/s). Incorporating SF into the HSSCC mix increased the dynamic modulus of elasticity (DME), while MSP incorporation resulted in a decrease in DME, with a systematic loss observed as the percentage of MSP increased. FA replacement had a similar effect, with the highest DME recorded in the control and S5F0M0 mixes. In terms of abrasion resistance, the S5F15M10 mix performed the best, with a thickness loss of just 1.2 mm, the lowest among all mixes. Scanning electron microscopy (FESEM) analysis revealed excellent surface morphology for the S5F15M10 mix, showcasing good interfacial transition zone (ITZ) characteristics, minimal cracks, and negligible voids, leading to a dense mortar matrix that contributed to the excellent mechanical performance. The energy dispersive X-ray spectroscopy (EDS) analysis confirmed that the mix had the lowest Ca/Si ratio, which correlated with the highest compressive strength, supporting the conclusion that a lower Ca/Si ratio contributes to improved concrete performance.

Khalil and Anwar (2015) investigated the carbonation behavior of concrete incorporating fly ash and silica fume as partial replacements for cement. The study used an M40 grade concrete mix with a mix ratio of 1:1.6:2.4 and a water-binder (w/b) ratio of 0.4. Concrete cubes (150 mm) were cast and cured for 28 days. Fly ash was consistently used to replace 25% of the cement, while silica fume was used at two levels, 5% and 10%. The results indicated that the compressive strength of the control mix (without supplementary cementitious materials) was 63 MPa. The compressive strength decreased by 5% when 25% fly ash was incorporated, and by 10% when 10% silica fume was added. Regarding carbonation depth, the control mix had a depth of 4 mm, which increased to 7.3 mm and 7.4 mm when 25% fly ash was used. For the silica fume mixes, the carbonation depth was 4.2 mm and 4.6 mm for 5% and 10% silica fume replacements, respectively.

Jiho Moon (2020) investigated the effects of partially replacing cement with fly ash, silica fume, and nano-silica on the carbonation depth and compressive strength of concrete. The study used M40 grade concrete with a mix ratio of 1:1.6:2 and a water-binder (w/b) ratio of 0.36, incorporating a water-reducing chemical admixture. Concrete cylinders (100 mm × 200 mm) were cast and cured for 28 days, and carbonation tests were conducted on prisms (100 mm × 100 mm × 400 mm). The compressive strength of the control mix was 48 MPa. The addition of 2% nano-silica resulted in a 2% increase in strength, while 15% fly ash and 3.5% silica fume led to 10% and 12% increases, respectively. Regarding carbonation depth, the control mix exhibited a depth of 4 mm, which increased to 6 mm with 15% fly ash. In contrast, the carbonation depth decreased by 1.5 mm and 1.4 mm with the inclusion of 3.5% silica fume and 2% nano-silica, respectively. These findings suggest that silica fume and nano-silica reduce carbonation depth, thereby enhancing the concrete's durability, while fly ash increases the carbonation depth compared to the control mix.

Leung et al. (2016) studied the sorptivity of self-compacting concrete (SCC) incorporating fly ash (FA) and silica fume (SF). The study involved two mix series: the first series contained fly ash alone, with 5 mixes having replacement levels ranging from 12.9% to 50%, while the second series included both silica fume and fly ash, with 4 mixes having FA replacement levels between 25% and 40%. The sorptivity coefficient (10^-4 g/mm²/min^1/2) was found to be highest for the higher replacement levels, with a value of 0.46 for 50% fly ash and 0.39 for 15% fly ash and 25% silica fume. The results showed an average reduction of 20.3% in water absorbed at all measured times when the OPC replacement by fly ash increased from 30% to 40% (comparing F4 and F5). However, when comparing F4 and FS2 (both with 30% replacement), the presence of silica fume had a more significant impact on reducing water absorption, leading to a 24.4% decrease. A further reduction of 25.2% was observed when comparing F5 and FS4 (both with 40% replacement). These findings highlight that silica fume is more effective in reducing water absorption in SCC. The highest compressive strength was recorded for the F125S10 mix (74.55 MPa), followed by the 12.9% FA mix (61 MPa). No clear correlation was found between sorptivity and the 28-day cube strength. The behavior of surface water absorption and compressive strength in SCC depends on the proportions of mineral admixtures and other environmental factors, with long-term concrete strength serving as a more reliable indicator of durability.

2.3 Utilization of Silica Fume and Ground Granulated Blast Furnace Slag along with other material:

Qureshi et al. (2020) investigated the strength and durability properties of quaternary blended concrete incorporating silica fume (SF), ground granulated blast furnace slag (GGBS), and rice husk ash (RHA). The specimens were cast and tested for mechanical properties, including compressive strength, tensile strength, and chloride penetration resistance. The concrete was designed for M40 grade, and the optimal mix was found to be 15% RHA, 10% SF, and 10% GGBS, replacing 50% of ordinary Portland cement (OPC). The results showed a 19% improvement in compressive strength and a 44% increase in tensile strength compared to the control mix. Chloride ion penetration (CP) resistance was enhanced by 20.46% with the inclusion of supplementary cementitious materials (SCMs) in the binder matrix. Additionally, 1% high-strength silica fume (HSF) improved the CP resistance by 2–7%. The combination of 30% GGBS and 1% HSF resulted in a significant improvement in CP resistance, with a 64–67% enhancement at 28 days. Furthermore, 1% HSF contributed to a 15–17% improvement in the alkali-aggregate reaction (AAR) of recycled aggregate concrete (RAC).

Maryam Hojati et al. (2022) investigated 3D-printable quaternary cementitious materials for sustainable development, focusing on mixture design and mechanical properties. The study involved 3D printing cylindrical specimens (150mm × 300mm) to assess printing quality. Four supplementary cementitious materials (SCMs)—metakaolin (MK), silica fume (SF), blast furnace slag (BFS), and sodium metasilicate (SM)—were used as partial replacements for cement. Two replicates were prepared for each mix, and the specimens were polished after 28 days to achieve smooth surfaces, reducing their size to 120mm × 120mm × 240mm. For comparison, control specimens were also cast and cut to similar dimensions (100mm × 100mm × 200mm). The optimal mixture, SF10 + BFS20 + SS2.5_WRA0.0_NC0.3, yielded an acceptable printing quality. The 28-day compressive strength of this mixture was 44.7 MPa, with a final setting time of 120 minutes. These results were attributed to the increase in the water-to-binder (W/B) ratio from 0.37 to 0.45, which was 22% higher than the BFS20 + SF10 + SS0.5_WRA0.3 mix. This change resulted from the elimination of water-reducing admixture (WRA) and the use of a larger quantity of accelerator (five times more than the BFS20 + SF10 + SS0.5_WRA0.3 mix), which shortened the setting time of the final printable mixture.

2.4 Utilization of Fly Ash and Ground Granulated Blast Furnace Slag along with other material:

Ganta Kiran Babu et al. (2023) investigated the mechanical properties and durability of quaternary blended geopolymer concrete (GPC) incorporating fly ash, ground granulated blast furnace slag (GGBS), metakaolin, and rice husk ash. The study focused on G40 and G60 concrete grades, evaluating compressive strength, flexural strength, split tensile strength, and durability parameters such as acid resistance, sorptivity, and chloride ion permeability. The results revealed that ternary blended mixes (fly ash, GGBS, and metakaolin) outperformed both binary and quaternary mixes in terms of mechanical and durability properties. The optimum mixes were identified as follows: For G40, FA50 GGBS30 MK20, and for G60, FA40 GGBS40 MK20. The compressive strength of both ternary mixes surpassed other combinations, with the highest compressive strengths of 46.26 MPa and 65.05 MPa for G40 and G60, respectively. After 28 days of acid immersion, compressive strength reduced by 14% for G40 and 9% for G60. Mass loss after immersion was minimal, at 5.95% for G40 and 5.57% for G60, the lowest among all mixes. Flexural strength values were 4.82 MPa for G40 and 5.78 MPa for G60, both higher than those of other mixes. Split tensile strength was also superior, with G40 achieving 3.44 MPa and G60 4.21 MPa. Both G40 and G60 ternary blends showed a similar trend in sorptivity, with coefficients of 0.41 and 0.38, respectively. Additionally, the lowest chloride penetration values were recorded for these mixes, at 1816 coulombs for G40 and 1650 coulombs for G60.

Bhunia et al. (2013) studied the effects of carbonation on the mechanical properties of plain concrete. M30-grade concrete was prepared with a mix ratio of 1:1.8:3.3 and a water-binder ratio (w/b) of 0.5. Concrete cubes of 100 mm size were cast and tested for compressive strength at 7 and 28 days of curing. Carbonation depth was measured at regular intervals of 2, 4, and 6 months. The carbonated zone was identified by spraying phenolphthalein solution on the fractured surfaces of the cubes. The results showed that the compressive strength of the control concrete at 7 days was 33.96 MPa, increasing to 35 MPa after 28 days. In terms of carbonation depth, the concrete exhibited a depth of 3 mm at 2 months, which increased to 5 mm at 4 months, and reached 14 mm after 6 months. These results demonstrate a progressive increase in carbonation depth over time, indicating that plain concrete becomes more susceptible to carbonation as it ages.

Ramzi et al. (2022) optimized the mixture proportions of quaternary blended cement mortars using the Taguchi method. The mixes incorporated ultra-fine treated palm oil fuel ash (u-TPOFA) in the range of 30-45%, Ground granulated blast furnace slag (GGBFS) between 12.5-20%, metakaolin (MK) from 7.5-15%, and a water-to-binder (W/B) ratio of 25-28% relative to Ordinary Portland Cement (OPC). The response factors evaluated included compressive strength (CS), porosity (P%), water absorption (Abs%), and thermogravimetric (TG) and X-ray diffraction (XRD) analyses. Using the L16 array in the Taguchi method, 16 experiments were conducted, and optimization was performed through analysis of variance (ANOVA). The optimum mix was determined to be 30% u-TPOFA, 17.5% GGBFS, 15% MK, and 25% W/B. The optimized mixture demonstrated significant improvements compared to plain cement mortar. Workability increased by 6%, while compressive strength improved by 99.02% at 7 days and 116.92% at 28 days. The porosity was reduced by 40% at both 7 and 28 days, and water absorption decreased by 45% at 28 days. Additionally, the cement content was reduced by 37.5%, from 882.22 kg/m^3 to 330.83 kg/m^3. The lower amount of portlandite formation during hydration and its consumption through pozzolanic reactions with supplementary cementitious materials (SCMs) contributed to the enhanced performance, driven by superior pozzolanic reaction kinetics.

Sakr and Bassuoni (2021) conducted an experimental study to evaluate the effects of partial cement replacement with Ground Granulated Blast Furnace Slag (GGBS) and Fly Ash on the compressive strength and carbonation of concrete. The study used M30-grade concrete with a mix ratio of 1:1.55:3 and a water-binder ratio (w/b) of 0.5. GGBS was used at replacement levels of 30% and 60%, while Fly Ash was used at 20% and 40% replacements. Concrete cubes of 100 mm size were cast and tested for compressive strength and carbonation depth. The results showed that the compressive strength of the control mix was 38 MPa at 28 days. For Fly Ash replacement, the compressive strength increased by 3% for 20% replacement but decreased by 5% for 40% replacement. For GGBS replacement, the compressive strength remained the same as the control mix for 30% replacement but decreased by 13% for 60% replacement. Regarding carbonation depth, the control concrete exhibited a carbonation depth of 3 mm after 28 days. The carbonation depth increased to 3.5 mm and 4 mm for 20% and 40% Fly Ash replacements, respectively. For GGBS replacement, the carbonation depth increased to 3.7 mm for 30% replacement and 8 mm for 60% replacement. These findings suggest that while Fly Ash and GGBS replacements had a moderate effect on compressive strength, both contributed to an increase in carbonation depth with higher carbonation observed for higher replacement levels, particularly for GGBS.

Table 2.1 Critical Review of Blended Concrete

Author name	Grade of concrete with mix proportion	Materials used and %replacement of cement	Parameters	Conclusions
ShreekanthBirgonda et. al., (2023)	M50	Induction furnace slag, SF, FA, GGBFS OPC57.5% GGBS30% FA10% SF2.5%	CS, STS, FS, Elastic modulus, Pull out bond strength.	Superior compressive strength of 46.80MPa with IFS aggregate which is 6% more than control mix. Split tensile strength of 4.12 MPa increased by 6% at 56 days. Flexural strength of 7.25MPa increased by 9% at 5 days. Elastic modulus of 35.2 GPa obtained at 56 days. Pull out bond strength of 15.9 MPa obtained at 56 days.
Ashok D. Chavan et. al. (2024)	M70	GGBS, FA, SF 25% GGBS, 15% FA, 10% SF replacing OPC	CS, RCPT, RCMT, Electrical Resistivity	Compressive strength increased by 8.5% at 28 days; improved durability. The compressive strength of concrete is 76 Mpa at 28 days curing period. Sika Viscocrete 5210N is incorporated at 1.5% of the total binder weight to enhance fluidity and retention. 510 charge passed in coulombs at 28 days.
Naitik Patel et al.,	M40	FA, GGBS, SF	CS	Binary blends show a drop in early and mid term strength compared to the control mix. Quaternary

(2016)		15% FA, 20% SF, 15% GGBS replacing 30% OPC		blend progressively outperform the control, with Mix (50 % OPC + 15 % FA + 20 % SF + 15 % GGBS) achieving the highest strengths at all ages (52 MPa at 7 days; 72 MPa at 28 days; 78 MPa at 56 days).
Hemant S. Chore et. al., (2020)	M40	90% OPC, 3.33 SF, 3.33GGBS, 3.33 FA	CS, FS, STS	For 28 days curing, it is seen that the strength obtained is 54.15 MPa which is 0.27% increase than the control mix with 25% replacement 8.34% each. Flexure strength of 10MPa was obtained by 10% replacement with 3.33% each. Indirect tensile strength was obtained by same mix as 4.8MPa
Ashika et.al., (2017)	M60, M80	GGBS, SF and FA FA20 GGBS25 SF10	Slump flow, U box test, T50 test, Water penetration, carbonation depth and mercury porosity test	Slump value: 652-710 mm for M60 and 670-720 mm for M80. T50 test: 2.4-2.5 sec for M60 and 2.5-2.7 sec for M80. Water permeability: 3.8-4.2mm for 7 days in M60 and 2.8-3.1 mm in M80 The total porosity of mercury intrusion is 5.768%, which means very low permeable.
Aamar Danish et al. (2024)	M60	Waste marble powder, fly ash, GGBS, Silica Fume, Metakaolin, River aggregate GGBS: FA: SF: MK = 12:4:1:1	CS, FS, durability, porosity, water absorption, Mass loss, acid resistance.	Mix achieves the highest compressive strength at both curing temperatures (63.25 MPa at 50°C and 83.23 MPa at 70°C). Flexural strength of 8.51 MPa and 11.03MPa at 50°C and 70°C. Lowest apparent porosity of 4.72% at 70°C. Lowest water absorption of 2.84%. Lowest sorptivity of 0.28 kg/m2. Lowest mass loss of 2.67% at 500°C. Mix 1:1:0.62 demonstrates Better acid resistance, especially under HCl and H_2SO_4 exposure, with lower mass loss and compressive strength loss.
Sridevi et. al., (2021)	M40 0.3-0.4	mS, FA, GGBS, Bacteria	Durability	Percentage decrease in water permeability is 35.97% (w/b 0.3) and 23.3% (w/b 0.4) between QBBSCC and QBSCC. Percentage decrease in RCPT permeability

		Bacillus Subtilus, 10% mS, 25% FA, 25% GGBFS		45.05% (w/b 0.3) and 30.52% (w/b 0.4) between QBBSCC and QBSCC.
Saresh Arya et. al., (2017)	M30	SF, FA, RHA 20FA10SF	CS, FS, TS	In all tests QBC strength is less than the control mix. Whereas, for Ternary mix of 20FA10SF got 3.6% more compressive strength, 18.7% more split tensile strength and 25.22% more flexure strength than Control mix.
RakeshChoudary et. al., (2021)	M50	WMS, FA, SF SF5 WMS10 FA15	Durability, CS and XRD analysis	Optimum mix (SF5 FA15 WMS10) shows the improved compressive strength of 62.56MPa which is 7MPa greater than control mix. Water permeability has 84.21% reduction in water penetration depth 15mm. The lowest value of chloride penetration depth was found in the FA35 mix. The value of chloride penetration depth was 72.37% lower than the Ref-2(SF5) mix. The SCC mix FA15WMS10 showed a carbonation depth of 1 mm at 90 days exposure period. The drying shrinkage value of the mix FA15WMS10 was lower by 27.78% than the Ref-1 (OPC) mix.
D. Praseeda et. al.,(2021)	M30	Cement, vitrified tiles powder, silica fume, fly ash 60%OPC, 25% VTP, 7% SF, 8% FA	CS, STS, FS, ultrasonic pulse velocity (UPV), microstructure (SEM, XRD, EDS), thermal stability.	The optimum mix exhibited a noticeable compressive strength of 39 MPa,. The split tensile strength of the blended mix is about 6% higher than the conventional concrete at 28 days of curing age. Flexural strength has increase 9% with respect to the reference mix. The values for all the mixes are above 5000 m/s in UPV test, which says that the mixes formulated are of excellent quality. The increase in the strength is attributed to the closed packing of the particles in refining the pore structure and altering the microstructure by densifying the ITZ.
Rakesh et.al., (2020)	M40	SF, MSP, FA	CS, STS, FS, UPV test, DME, Abrasion resistance and	14.64% higher compressive strength compared to control mix. Flexure and split tensile strength was increased by 10.6% and 18.77%. Pull off strength was increased by 42.17%. Max UPV value of 5405 m/s is

	SF5F15M 10		Microstructural properties.	obtained. DME value is higher for control and SF5 mix. Abrasion resistance was higher with just 1.2 mm thickness loss. FESEM analysis shown very good ITZ characteristics without any crack.
Niragi Dave (2017)	M40	50% OPC, 30% FA, 10% SF, 10% MK	CS, FSand rapid chloride permeability test, Sulfate resistance, Ultra Pulse Velocity Test.	Compressive strength, flexural and tensile strengths 25%, 10% and 11.2% higher compared to control mix. The maximum ultrasonic pulse velocity (UPV) was recorded as 6172 m/s. At the age between 28 and 365days .the chloride permeability charge passes has decreased 78.2%. Maximum sulfate expansion values of 0.48% (365days)in plain concrete and 0.12% (in binary concrete) to 0.03% in quaternary concrete were obtained.
Khalil and Anwar (2015)	w/b=0.4, 0.5 and 0.6	25% FA constant replacement SF as 5% to 15% replacement.	CS Carbonation	Compressive strength for 0.4 w/b nominal mix was 63MPa and decreased to 14% and 4.7%. The carbonation depth was 4mm and increased to 7.3mm, 7.4mm for 25% of fly ash, and 4.2mm and 4.6mm for silica fume replacements.
H.Y. Leung et. al., (2016)	w/b = 0.38 FA50 SF15 FA25	FA, SF FA50 SF15 FA25	Sorpitivity, CS	It is observed that, at the same OPC replacement level, F30% gives 31.8% reduction in sorptivity while F25S5 shows 54.2% decrease. Highest compressive strength was shown by F125S10 with 74.55MPa and 12.9% FA with 61 MPa.
L.A. Qureshi et al. (2020)	M40	RHA, SF, GGBS 15% RHA, 10% SF, 10% GGBS replacing 50% OPC	CS, TS, Chloride Penetration Resistance	Compressive strength improved by 19%; tensile strength increased by 44%. Chloride ion penetration (CP) resistance was enhanced by 20.46% with the SCM inclusion in the binder matrix. 1% HSF inclusion improved the CP resistance by about 2–7%.Coupling 30%GGBS and 1% HSF improved the CP resistance by 64 and 67% at 28 days.1% of HSF improved the AAR of RAC by 15–17%
Maryam Hojati et. al. (2022)	M50	OPC, BFS,	CS,	Compressive strength of 57.11 MPa (cast specimens), 38.71 MPa (longitudinal 3D print specimems), 26.25

		SF, sodium metasilicate, nanoclay BFS20+SF10+SS2.5+NC0.3	flowability, Elastic modulus	MPa (perpendicular 3D print). Measured Elastic modulus as 14.88GPa in Cast specimen, 15.04GPa (longitudinal direction) and 20.97GPa (perpendicular direction).
Ganta Kiran Babuet al.(2023)	G40, G60 For G40: FA50 GGBS30 MK20 For G60: FA40 GGBS40 MK20	Fly ash, GGBS, metakaolin, rice husk ash	CS, FS,TS, durability (acid resistance, sorptivity, chloride ion permeability), microstructural analysis (SEM, XRD).	Highest compressive strength of 46.26MPa and 65.05MPa were shown by G40 and G60 mixes respectively which reduced by 14% and 9% after immersion in acid for 28 days. Mass loss (%) after 28 days immersion is 5.95 and 5.57 are lowest. Flexural strength of 4.82MPa and 5.78MPa obtained, greater than all other. Split tensile strength of 3.44MPa and 4.21MPa obtained. Both G40 and G60 ternary blended Geopolymer Concrete showed the same trend in sorptivity with coefficient of 0.41 and 0.38 . Lowest chloride penetration of 1816 coulombs and 1650 coulombs were obtained.
Bhunia et. al. (2013)	M30, w/b= 0.5	OPC	CS and Carbonation	The increases in strength up to 35 MPa for 28 days. Carbonation for 2 months is 3 mm increased to 5 mm and 14 mm for 4 and 6 months.
Ramzi J. Shaladi (2022)	M40	30% u-TPOFA, 17.5% GGBFS, 15% MK replacing 62.5% OPC	CS, Porosity, Water Absorption	Workability increased by 6%, while compressive strength improved by 99.02% at 7 days and 116.92% at 28 days. The porosity was reduced by 40% at both 7 and 28 days, and water absorption decreased by 45% at 28 days. Additionally, the cement content was reduced by 37.5%, from 882.22 kg/m³ to 330.83 kg/m³.
Sakr and Bassuoni (2021)	M30 w/b= 0.4, 0.5 and 0.6.	FA as 20% and 40% replacement to OPC GGBS as	Carbonation CS	For 28 days compressive strength was 45 MPa and increased up to 25% and 36% for 40% replacement of Fly ash and 60% replacement of GGBS. The carbonation depth was increased to 3.5 mm and 4 mm for 20% and 40% replacement of fly ash and the depth

		replacement of 30% and 60%.		of carbonation was increased to 3.7 mm and 8mm for 30% and 60% replacement of GGBS.
Jiho Moon (2020)	M40 w/b= 0.36 mix ratio of 1:1.6:2	15% FA, 3.5% SF, and 2%NS as the replacements for OPC	CS Carbonation	Compressive strength was 48MPa and increased up to 2%, 10%, and 12% for 2% nano-silica,15% Fly ash, and 3.5% silica fume replacements. Carbonation depth was increased to 6mm for 15% Fly ash concrete and decreased by 1.5mm and 1.4mm for 3.5% of silica fume and 2% of nano silica replacements.

*SF- Silica fume, FA- Fly Ash, GGBS-Ground Granulated Blast Furnace Slag ,MK- Metakaolin, mS- Micro silica, AF- Alccofine, RHA- Rice Husk Ash, GQD- Granite Quarry Dust, LP- Lime powder, Pu- Pumice, WMS- Waste Marble Slurry, VTP- Vitrified Tiles powder, NP- Natural Pozzolan CS- Compressive Strength, FS- Flexural Strength, TS- Tensile Strength, UPVT- Ultrasonic Pulse Velocity Test, TGA- Thermogravimetric Analysis, CPT- Chloride penetration test, XRD - X-Ray Diffraction analysis

3.Conclusion:

The literature review clearly illustrates that replacing cement with industrial by-products such as Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Silica Fume (SF), Metakaolin (MK), Rice Husk Ash (RHA), Waste Marble Powder (WMP), and others can significantly enhance the performance of concrete. Studies consistently show that binary, ternary, and quaternary blends incorporating these materials improve compressive strength, flexural strength, split tensile strength, elastic modulus, durability, resistance to chloride penetration, carbonation resistance, and reduce permeability. Based on the findings from the reviewed literature, the following conclusions can be drawn:

Compressive Strength:

- Almost all studies reported an increase in compressive strength with the use of Fly Ash, GGBS, Silica Fume, Metakaolin, RHA, and VTP, particularly in optimized ternary and quaternary blends.
- Blends with FA inclusion increased the compressive strength (CS) by up to 25%, with GGBS contributing an increase of 8.5-25%, SF by 10-15%, MK by up to 25%, RHA by up to 19%, and VTP by up to 15%.

Flexural and Split Tensile Strength:

- Flexural strength improved significantly with all key supplementary cementitious materials (SCMs). Fly Ash increased flexural strength by up to 25.22%, GGBS by 9%, and SF by 10.6%. MK and RHA each enhanced flexural strength by around 10%, while VTP (25% replacement) showed a 10% increase over the control mix.

- Split tensile strength saw notable gains as well. Fly Ash increased tensile strength by up to 18.7%, SF contributed around an 18.77% gain, MK enhanced tensile strength by 11.2%, and RHA led to the highest increase of 44%. Vitrified Tiles Powder (25% replacement) improved tensile strength by 6% at 28 days.

Workability:

- Blended mixes generally exhibited a slump reduction of 20-50 mm compared to the control mix. This is due to the increased fines and higher water demand in blended concrete, which typically results in a lower standard slump than the control mix.

Durability:

- Water permeability decreased by an average of 35% to 85% compared to control mixes, indicating better resistance to water ingress.
- Chloride ion penetration resistance showed significant improvement, with some quaternary blends reducing the charge passed by over 70%.
- Carbonation depth was consistently lower in quaternary mixes, often under 4 mm, compared to the control mixes, where carbonation depths reached up to 7 mm.
- Porosity decreased by 20–40%, indicating a denser and more robust matrix with improved microstructure.
- Fly Ash and GGBS contribute to enhanced durability by forming additional calcium silicate hydrate (C-S-H) gel, which reduces porosity and improves resistance to chloride and sulfate attack. Silica Fume, due to its ultra-fine particle size, fills micro voids and densifies the interfacial transition zone, significantly reducing permeability. Metakaolin and Rice Husk Ash provide high pozzolanic activity and micro-filling ability, which further reduce water ingress and enhance chemical resistance. Vitrified Tiles Powder enhances impermeability through its ceramic nature and strengthens the concrete microstructure by reducing voids and shrinkage.

In conclusion, the incorporation of industrial by-products such as FA, GGBS, SF, MK, RHA and VTP significantly improves the mechanical and durability properties of concrete, making it a more sustainable and high-performance material.

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