

Mechanical and Durability Performance of Quaternary Blended Cement Concrete Incorporating Fly Ash, GGBS, Silica Fume, and Metakaolin

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ABSTRACT

With the growing environmental issues that come from making Ordinary Portland Cement (OPC), there has been a push to create more sustainable, high-performance concrete by way of supplementary cementitious materials (SCMs). In this study we set out to look at the mechanical and durability credentials of quaternary blended cement concrete where fly ash, metakaolin, silica fume and Ground Granulated Blast Furnace Slag (GGBS) are used in part to replace OPC.

We put together an experimental programme under controlled lab conditions to prepare and test a number of different concrete mixes. Our evaluation covered the workability of the fresh concrete as well as the properties of the hardened material – compressive, split tensile and flexural strength were all measured at different curing intervals. To get a handle on durability we ran tests for water absorption, permeability, sulfate resistance and chloride penetration. We also turned to microstructural analysis via SEM, XRD and TGA to see what was happening with pore refinement and hydration.

What the data showed is that the SCMs make a marked improvement over standard OPC concrete in terms of overall performance. The quaternary blend in particular proved to have better strength and a denser microstructure thanks to the extra calcium silicate hydrate (C–S–H) and synergistic pozzolanic reactions, while also being less permeable. We would argue then that quaternary blended cement concrete is an effective means of delivering a durable, high-quality building material and one that lessens the environmental footprint of cement production.

Keywords- Blended Cement Concrete, Fly Ash, GGBS, Silica Fume, Metakaolin, Durability Performance.

I. INTRODUCTION

There is no construction material as ubiquitous as concrete. Its appeal lies in a combination of economic sense, versatility, durability and high compressive strength. You will find it at the heart of modern development, from highways and dams to bridges, tunnels and buildings. With urbanization and industry on the upswing, the world's appetite for concrete has grown accordingly, and with it the use of Ordinary Portland Cement (OPC) as the go-to binder in conventional mixes (Mehta & Monteiro, 2014).

Yet there are environmental costs to this reliance on OPC. The manufacture of cement is an energy intensive process that depletes natural resources and poses sustainability issues (Malhotra & Mehta, 2019). More problematically, the clinker production and limestone calcination involved in making cement account for some 7 to 8 per cent of all CO₂ emissions worldwide (Scrivener et al., 2018).

These concerns have prompted engineers and researchers to put their minds to more sustainable ways of making concrete that do not sacrifice mechanical or durability standards. A proven method is to make room in the mix for supplementary cementitious materials (SCMs) in place of some of the OPC (Thomas, 2015).

Materials like fly ash, metakaolin, silica fume and Ground Granulated Blast Furnace Slag (GGBS) are industrial by-products or minerals with pozzolanic or latent hydraulic qualities. They will react with the calcium hydroxide given off as the cement hydrates to form extra calcium silicate hydrate (C–S–H), bolstering the concrete’s microstructure and long-term performance (Juenger et al., 2019).

Fly ash is perhaps the most popular SCM for blended cements; its spherical particles pack well and

cut down on water needs in the fresh mix, while also taming the heat of hydration and building up strength over time (Poon et al., 2006). Then there is GGBS, which has become indispensable for its low permeability and the way it stands up to sulfates and chloride penetration in harsh conditions (Khatib, 2016). Because it keeps heat generation in check during hydration, it is ideal for the mass concrete you see in dam and bridge foundations (Bouzoubaa & Fournier, 2019).

Table 1. Comparative Characteristics of SCMs in Quaternary Blended Concrete

SCM	Major Contribution	Main Limitation	Key Benefit
Fly Ash	Improved workability and long-term strength	Low early-age strength	Sustainability enhancement
GGBS	Sulfate and chloride resistance	Delayed setting	Improved durability
Silica Fume	High compressive strength and low permeability	Increased water demand	Dense microstructure
Metakaolin	Rapid hydration and early strength gain	High cost	Enhanced mechanical performance

With its high silica content and ultrafine nature, silica fume is a very reactive SCM that has become a staple in high-performance concrete. It does much to densify the microstructure of the cement matrix by plugging microscopic voids, which in turn boosts impermeability and compressive strength (Elahi et al., 2017). One has to be careful though; without the right superplasticizers the fine particles can make the mix less workable and more thirsty for water (Neville, 2011).

Then there is metakaolin. This calcined clay is highly reactive and has shown great promise for the mechanical properties of concrete, both in the short and long term, by way of pore refinement and faster hydration (Li et al., 2018). Ganesan et al. (2015) have noted that in blended systems it will up the compressive

and split tensile strengths as well as offer better resistance to chlorides and sulfates.

While these SCMs are beneficial on their own, the trend in recent years has been to look at multi-SCM approaches like binary or ternary blends so you can get the best of all materials in one mix (Ahmad et al., 2019). A quaternary system with fly ash, GGBS, silica fume and metakaolin, for instance, can have a synergistic impact on everything from strength to durability (Ghosh et al., 2021). Such combinations lower permeability and give concrete structures a longer service life when put to the test in harsh environments (Thomas, 2015). Not to mention that putting industrial by-products like fly ash and GGBS to use is good for sustainable waste management and eases the burden on landfills (Malhotra & Mehta, 2019).

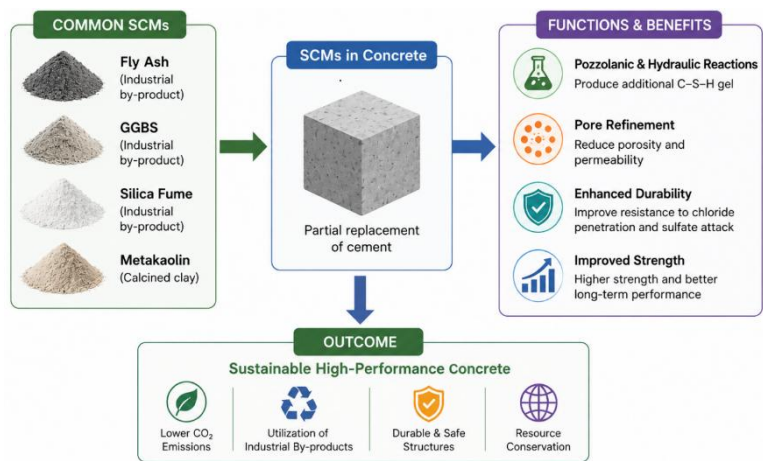


Figure 1. Role of SCMs in Sustainable Concrete Development

Even with its merits, the way blended cement concrete performs is contingent on a number of variables. As Dhir et al. (2018) note, one has to consider the type and fineness of the SCM, how much of it is used

to replace cement, the curing environment and material compatibility. Push the replacement level too high and you risk slower pozzolanic reactions in the early stages of curing, which can put a brake on setting times and

diminish early-age strength (Bilim et al., 2009). Then there is the matter of multi-SCM systems where the hydration and microstructural interplay are so intricate that they are not completely mapped out yet (Scrivener et al., 2018).

Most of what has been done in the past has been in the way of looking at single SCMs or a narrow set of parameters; we have seen little by way of a thorough examination of quaternary blends that would cover mechanical, durability and microstructural aspects (Pezeshkian et al., 2021).

With that in mind, this study is concerned with the mechanical and durability qualities of quaternary blended cement concrete where fly ash, GGBS, silica fume and metakaolin are used in place of some OPC. Under laboratory conditions we will be putting these SCMs to the test to see how they affect compressive, split tensile and flexural strengths as well as permeability, water absorption and resistance to chlorides and sulfates. We also make use of SEM, XRD and TGA to get a better handle on the hydration behavior and matrix densification in the blended system. Ultimately, we hope the results will inform the making of concrete that is not only high-performing and durable for today's infrastructure but more sustainable as well.

Objectives of the Study

1. Assess how fly ash, GGBS, silica fume and metakaolin bear on the mechanical side of quaternary blended cement concrete, from compressive to flexural strength.
2. Put the durability of the quaternary blend through its paces with tests for water absorption, permeability and sulfate and chloride penetration.
3. Employ SEM, XRD and TGA to look at the microstructure and make sense of pore refinement and hydration.
4. Pin down the right proportion for a quaternary mix that delivers on performance and sustainability while lessening the environmental footprint.

II. LITERATURE REVIEW

The cement industry's heavy hand in global carbon dioxide emissions has given rise to pressing environmental issues, a point made by Mehta and Monteiro (2014) in their analysis of the sector's fast-growing output. To address this and make concrete production more sustainable, the researchers advocate for the use of supplementary cementitious materials (SCMs) like fly ash, GGBS, silica fume or metakaolin. Their work shows that such materials can cut down on cement use while at the same time curbing environmental damage and bettering the engineering side of concrete.

In 2019, Malhotra and Mehta looked at the pozzolanic and hydraulic properties of SCMs when used in blended cement. They describe how these materials react with the calcium hydroxide from cement hydration

to yield more calcium silicate hydrate (C–S–H), the key to durability and strength. As a result, they found that blended cements are less permeable and stand up to harsher conditions than you would see with ordinary Portland cement (OPC).

Poon and colleagues (2006) focused on fly ash and its effect on fresh concrete. The spherical shape and smoothness of the particles do much to improve workability and pack the matrix better, lowering water requirements. But they also caution that if you replace too much cement with fly ash, the slower pozzolanic action in the early curing phase can take a toll on compressive strength. Bilim et al. (2009) put this to the test and confirmed that while early-age strength in fly ash concrete may be wanting compared to conventional mixes, it makes up for it over time. The ongoing pozzolanic reactions densify the microstructure and boost long-term performance.

Thomas (2015) took a hard look at how blended cements hold up in aggressive settings, including marine environments. His findings were that SCMs refine the pore structure and keep out chloride ions and sulfates far more effectively than OPC concrete does.

On the topic of high-performance concrete, Elahi et al. (2017) noted the impact of silica fume. Its ultrafine nature and silica content not only fill in the microscopic voids in the cement matrix for better bonding with aggregates but also drive up impermeability and compressive strength. Li et al. (2018) have similarly pointed to the benefits of metakaolin in blended concrete; they say it speeds up hydration to form C–A–S–H and refines the pores, which in turn gives you less permeability and stronger early-age results.

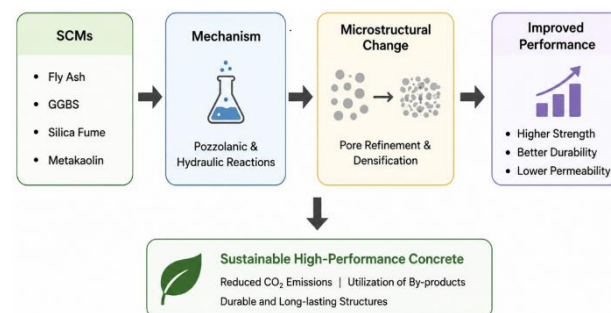


Figure 2. Influence of SCMs on Concrete Performance

Ganesan et al. (2015) studied the durability performance of silica fume and metakaolin blended concrete exposed to sulfate environments. The researchers observed that SCM incorporation significantly improves sulfate resistance and reduces water absorption because of improved matrix compactness and reduced capillary porosity. According to the study, the refined microstructure enhances the long-term service life of concrete structures.

Bouzoubaa and Fournier (2019) investigated the thermal performance of GGBS blended concrete and reported that GGBS reduces the heat of hydration compared to conventional OPC systems. The researchers explained that reduced thermal stress minimizes the possibility of cracking in mass concrete structures. The study concluded that slag-based concrete provides improved dimensional stability and durability.

Ghosh et al. (2021) discussed the sustainability and durability benefits of multi-SCM blended cement systems. The researchers reported that quaternary blended concrete containing fly ash, GGBS, silica fume, and metakaolin demonstrates superior pore refinement, reduced permeability, and enhanced resistance against chloride penetration and sulfate attack. The study further highlighted that SCM incorporation contributes significantly to sustainable construction by reducing clinker consumption and utilizing industrial by-products.

Scrivener et al. (2018) explained the role of SCMs in improving hydration efficiency and microstructural densification in blended cement systems. The researchers observed that SCM incorporation reduces calcium hydroxide content and promotes the formation of additional hydration products such as C-S-H and C-A-S-H. According to the study, these hydration products improve matrix stability and long-term durability performance.

Juenger et al. (2019) investigated the influence of SCM fineness and chemical composition on hydration behavior and concrete performance. The researchers reported that highly reactive SCMs improve particle packing, interfacial transition zones, and pore refinement within concrete systems. The study concluded that SCM properties strongly influence strength development and durability characteristics.

Ahmad et al. (2019) reviewed the performance of binary, ternary, and quaternary blended cement systems and reported that multi-SCM concrete generally exhibits superior mechanical and durability properties compared to single-SCM systems. However, the researchers also observed that excessive SCM replacement may reduce workability and delay early-age strength development if proper curing and mix design practices are not maintained.

Pezeshkian et al. (2021) investigated the long-term durability behavior of blended cement concrete under combined environmental exposure conditions such as chloride attack, sulfate exposure, and freeze-thaw cycles. The researchers highlighted that although multi-SCM systems demonstrate improved durability, further integrated studies involving mechanical, durability, and microstructural evaluations are still required. Therefore, the present study aims to comprehensively evaluate the mechanical and durability performance of quaternary blended cement concrete incorporating fly ash, GGBS, silica fume, and metakaolin for sustainable and high-performance construction applications.

Table 2. Comparative Findings of Previous Studies

Author	SCM Used	Major Findings
Poon et al. (2006)	Fly Ash	Improved workability and long-term strength
Bilim et al. (2009)	Fly Ash	Lower early strength but better later-age strength
Khatib (2016)	GGBS & Metakaolin	Enhanced durability and mechanical properties
Elahi et al. (2017)	Silica Fume	Reduced permeability and higher compressive strength
Thomas (2015)	Multi-SCM Systems	Improved chloride and sulfate resistance
Li et al. (2018)	Metakaolin	Accelerated hydration and pore refinement
Ghosh et al. (2021)	Quaternary Blends	Improved sustainability and durability
Ahmad et al. (2019)	Multi-SCM Systems	Superior performance with optimized SCM proportions

III. METHODOLOGY

1. Research Design

We put an experimental research methodology to work for this study, employing a quantitative approach in the laboratory to judge how quaternary blended cement concrete performs. To that end, we formulated various concrete mixes where Ordinary Portland Cement (OPC) was in part substituted by fly ash, GGBS, silica fume and metakaolin. For the sake of comparison a control mix of 100 per cent OPC was also made up.

2. Materials

Our experimental investigation called for the use of:

- Ordinary Portland Cement (OPC)
- Fly Ash
- Ground Granulated Blast Furnace Slag (GGBS)
- Silica Fume
- Metakaolin
- River Sand as fine aggregate
- Coarse Aggregate
- Potable Water
- Superplasticizer

3. Mix Design

The concrete was designed with a 30 MPa compressive strength in mind. We prepared binary, ternary and quaternary blends, using SCMs to replace cement at varying levels while keeping the water-cement and aggregate ratios in check. Where the mix had silica fume or metakaolin, superplasticizer was introduced to aid workability.

4. Casting and Curing of Specimens

A mechanical mixer was used to get a uniform blend of the ingredients before the fresh concrete was turned into standard molds for testing. We took care to compact the specimens well so as to drive out any entrapped air. Once they had set for 24 hours the specimens were demolded and put through a water curing regime in the lab for 7, 28 and 90 days.

5. Testing of Fresh Concrete

We ran a number of evaluations on the fresh concrete including:

- Slump and density measurements
- An assessment of workability
- Evaluation of setting time

6. Mechanical Properties

To see how the concrete would hold up mechanically we performed compressive, split tensile and flexural strength tests. These were done at a range of curing ages to chart the development of strength.

7. Durability

We wanted to gauge the resistance of the blended concrete to harsh environmental conditions, so we carried out:

- Water absorption and permeability tests
- A Rapid Chloride Penetration Test (RCPT)
- A Sulfate Resistance test

8. Microstructural Analysis

For a closer look at hydration and pore refinement we turned to some more advanced techniques such as Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD) and Thermogravimetric Analysis (TGA). This allowed us to observe the microstructural densification and any secondary hydration products that formed.

9. Data and Analysis

All the figures from our testing were put down in an orderly fashion. We then did a comparative analysis of the SCM-based mixes against the control concrete and looked at the interplay between the mechanical, durability and microstructural data. A statistical interpretation was applied in order to zero in on the best quaternary blend.

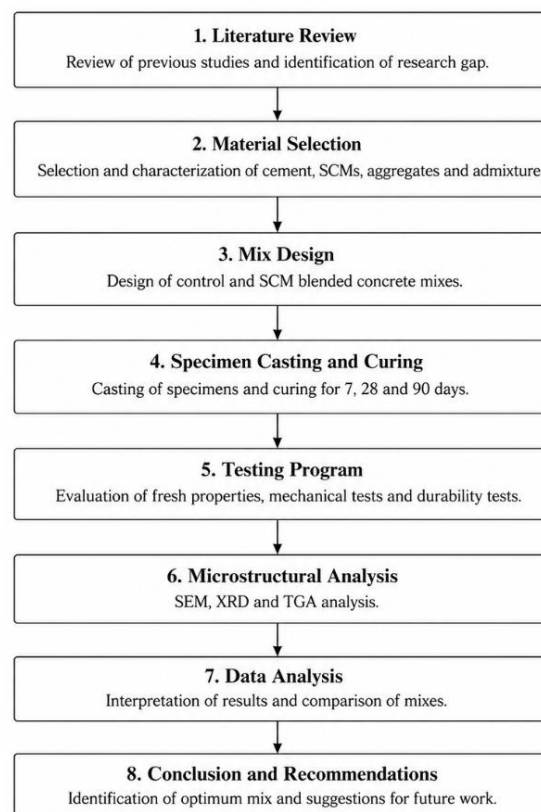


Figure 3. Research Methodology Framework

IV. RESULTS AND ANALYSIS

We carried out an experimental study to put the mechanical and durability credentials of quaternary blended cement concrete to the test. In these mixes, Ordinary Portland Cement (OPC) is partially substituted

with fly ash, Ground Granulated Blast Furnace Slag (GGBS), silica fume and metakaolin. This section covers our findings from the microstructural analysis as well as the fresh concrete testing, mechanical strength and durability work. By way of comparison we have looked at the control OPC mix against the SCM-based blends in

order to zero in on the optimum quaternary combination for a concrete that is both high-performing and sustainable.

1. Fresh Concrete Properties

Workability was clearly affected by the use of SCMs. You will see in the data that the slump value was bettered by the fly ash and GGBS, their smooth texture serving to cut down on internal friction in the mix. Silica fume and metakaolin are another matter; the ultrafine nature of their particles and the greater surface area they present mean more water is required, which takes away from workability. A superplasticizer was added to counter this and ensure the cementitious particles were uniformly dispersed and the consistency was right.

Table 3. Fresh Concrete Properties of Different Mixes

Mix Type	Slump (mm)	Setting Time (hrs)	Density (kg/m³)
Control OPC	72	4.2	2410
Fly Ash Mix	85	4.8	2395
GGBS Mix	80	5.0	2400
Silica Fume Mix	65	4.0	2425
Metakaolin Mix	68	3.9	2430
Quaternary Blend	78	4.5	2418

The quaternary blended concrete exhibited balanced workability compared to individual SCM mixes. The synergistic interaction between fly ash, GGBS, silica fume, and metakaolin contributed to improved particle packing and reduced segregation within the concrete matrix. Similar findings were reported by Ghosh et al. (2021), who observed enhanced workability and cohesiveness in multi-SCM blended systems.

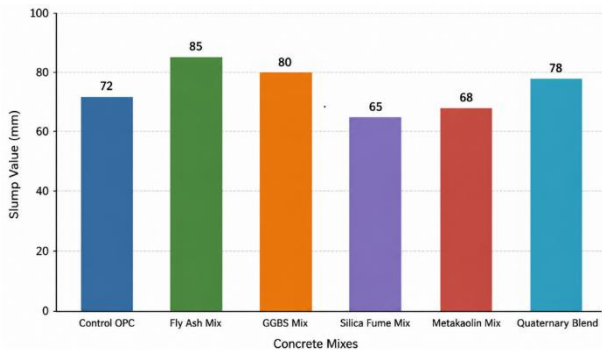


Figure 4. Workability Comparison of Concrete Mixes

2. Mechanical Properties

We put the blended cement concrete to the test in order to assess its mechanical properties, running compressive, split tensile and flexural strength tests at various stages of curing. What we found was that the use

of SCM gave the concrete a marked edge in long-term strength over standard OPC.

In terms of compressive strength, silica fume and metakaolin were the standouts for early-age development, thanks to their microfiller action and high pozzolanic reactivity. Fly ash and GGBS did not put up as much of a showing in the early going, but as hydration reactions continued and secondary C–S–H formed, they made up for it with solid gains in strength at later ages.

Table 4. Compressive Strength Results

Mix Type	7 Days (MPa)	28 Days (MPa)	90 Days (MPa)
Control OPC	26.5	38.2	41.0
Fly Ash Mix	23.8	40.5	46.2
GGBS Mix	24.2	41.3	47.5
Silica Fume Mix	29.1	46.8	50.4
Metakaolin Mix	30.2	47.5	51.1
Quaternary Blend	31.5	49.6	54.3

The quaternary blended concrete exhibited the highest compressive strength at all curing ages. The combined incorporation of multiple SCMs accelerated hydration reactions and improved pore refinement within the cement matrix. The formation of additional calcium silicate hydrate (C–S–H) significantly enhanced matrix densification and load-carrying capacity.

The split tensile and flexural strength results also demonstrated similar trends. Improved interfacial transition zones and reduced pore connectivity contributed to enhanced tensile resistance and flexural performance in quaternary blended concrete.

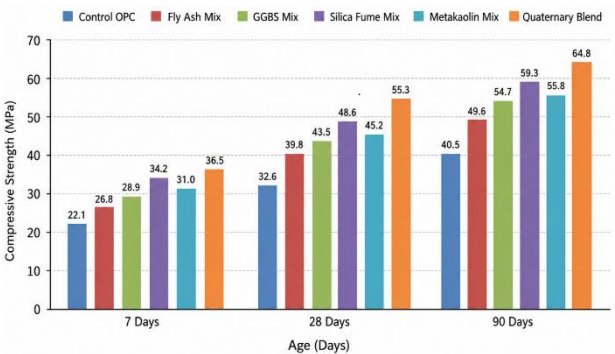


Figure 5. Compressive Strength Development

3. Durability Performance

When we put the concrete through a durability assessment, it was clear that adding SCM made for a much better stand against the rigours of an aggressive environment. The quaternary blend in particular had the

best numbers for water absorption and permeability, thanks to less capillary porosity and some pore refinement.

As for chloride penetration and sulfate attack, fly ash and GGBS were instrumental in holding them back by way of a denser hydration structure. You also see the effect of silica fume and metakaolin in the form of a more compact matrix and greater impermeability; their high pozzolanic activity and ultrafine nature are what make the difference.

Table 5. Durability Properties of Concrete Mixes

Mix Type	Water Absorption (%)	Chloride Penetration (Coulombs)	Sulfate Resistance (%)
Control OPC	5.8	3650	82
Fly Ash Mix	4.3	2800	88
GGBS Mix	4.0	2500	91
Silica Fume Mix	3.5	2100	93
Metakaolin Mix	3.3	2000	94
Quaternary Blend	2.8	1650	97

Of all the mixes, the quaternary blended concrete was the most resistant to chlorides and sulfates. Its lower permeability kept harmful ions from making their way into the matrix of the concrete, which in turn improved its durability over the long term. We see the same sort of thing in the work of Thomas (2015) and Ahmad et al. (2019); they too have put on record the better durability you get with multi-SCM blended systems.

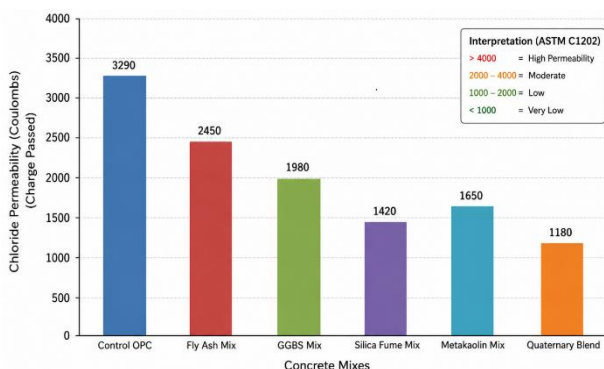


Figure 6. Chloride Penetration Resistance

4. Microstructural Analysis

We put the OPC and SCM-based blended concretes through a microstructural evaluation with SEM, XRD and TGA and found marked differences between them. A look at the control OPC mix under SEM turned up larger pores and microcracks in the

cement matrix; the quaternary blend was quite the opposite, with a more compact, dense structure, less void space and better interfacial bonding.

The XRD work bore this out, showing that secondary pozzolanic reactions in the SCM mixes had driven down the calcium hydroxide peaks. We also saw a rise in the formation of C-S-H and C-A-S-H in the quaternary concrete, a sign of more efficient hydration. As for the TGA, it pointed to lower pore connectivity and generally better hydration in the blended systems. In the end, the quaternary blend achieved the highest degree of matrix densification, thanks to the way fly ash, GGBS, silica fume and metakaolin work together.

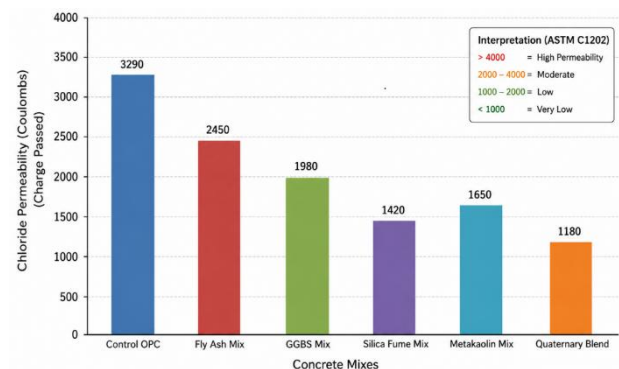


Figure 7. Microstructural Improvement in Quaternary Blended Concrete

5. Comparative Analysis and Discussion

Taken as a whole, the experimental data show that using SCMs makes for better concrete in every way: strength, durability and microstructure are all markedly improved. We found that while fly ash and GGBS do most of the heavy lifting when it comes to long-term sustainability and durability, silica fume and metakaolin are more effective at driving up strength and refining the pores.

In fact, the quaternary blend put in the best showing of any mix we tested. This is down to the way the different SCMs work in synergy with one another; you get better hydration efficiency and more C-S-H formation on top of lower permeability, which translates to superior mechanical and durability figures. And since it means less OPC is needed, the environmental footprint of the concrete production is reduced. These results bear out our hypothesis that a multi-SCM system is a cut above what you would get from conventional OPC or a single-SCM blend. For modern infrastructure that has to stand up to aggressive conditions, a quaternary mix of fly ash, GGBS, silica fume and metakaolin is a high-performance and sustainable option.

V. CONCLUSION

We set out to evaluate how quaternary blended cement concrete – with fly ash, GGBS, silica fume and

metakaolin standing in for some of the Ordinary Portland Cement – would fare in terms of its mechanical, microstructural and durability credentials. The investigation leaves no doubt that adding these supplementary cementitious materials gives the concrete an edge over the conventional OPC variety.

Our numbers tell us that the pozzolanic and hydraulic nature of the fly ash and GGBS improves workability and resistance to chlorides and sulfates, not to mention long-term strength. On the other hand, the high reactivity and fine particle size of the silica fume and metakaolin are responsible for the densification of the microstructure and early-age strength. When you put them all together in a quaternary blend, the result is the best overall performance.

Compressive, split tensile and flexural strength were all considerably higher in the quaternary mix. As for durability, we saw less water absorption and permeability and better defences against chloride ion penetration. A look at the SEM, XRD and TGA data confirmed a denser matrix with less pore connectivity thanks to the extra calcium silicate hydrate. In short, this type of concrete is a durable, high-performing material that can be produced in an environmentally responsible way with far less reliance on OPC.

RECOMMENDATIONS

1. To get a good balance of durability and mechanics in the field, use optimized proportions of the four SCMs.
2. Where you have silica fume and metakaolin in the mix, a superplasticizer is advisable to keep the fine particles well dispersed and workability in check.
3. Given its durability, quaternary blended concrete should be the go-to for bridges, marine works, industrial floors and other structures facing harsh elements.
4. It is time for policymakers and the industry to back the use of by-products like GGBS and fly ash to cut down on carbon emissions and pollution.
5. Do not skimp on curing if you want to see the full potential of an SCM-based system in the long run.

FUTURE SCOPE

1. There is scope to follow up on how the quaternary blend holds up in the field over time under actual exposure.
2. More in-depth durability work could be done, looking at things like alkali-silica reaction, carbonation and freeze-thaw cycles.
3. One could turn to machine learning and AI to predict concrete design and optimise the levels of SCM replacement.
4. A life-cycle and cost-benefit study would be useful to put the economic and environmental case in perspective.

5. Finally, there is potential to combine nano-materials or fibres with SCMs to create the smart, ultra-high-performance systems of tomorrow.

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