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Experimental study on Fresh and Hardened Properties of Quaternary Blended Cementitious Concrete for Sustainability

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Abstract. This experimental study focuses on Quaternary blended cementitious concrete (QBC) with different proportion of Ordinary Portland Cement (OPC), Fly Ash (FA), Metakaolin (MK) and Ground Granulated Blast-Furnace Slag (GGBFS). QBC performance attributes were assessed with workability, initial-final setting time, and their consistency based on standard tests that revealed improvements in handling fresh QBC. To prove the toughness of the concrete in the hardened stage, compressive strength, flexural strength and split tensile tests at 7, 14 and 28days were performed. The results showed that the Quaternary mixes improved both fresh and hardened properties from 1% to 3%. Important factors concluded by all these results indicate that the quaternary mixed cementitious concrete can also lead to high performance application and it can also give long-term benefit without damaging structural efficiency and can be considered as sustainable material. Another finding of the study is about mechanical performance of QBC which gives equal performance as conventional concrete by incorporating SCM under different percentages. In this experiment, it is clearly observed that the addition of MK and increase in GGBS % and incorporating FA really enhances the improvement of the concrete with respect to its fresh and hardened properties.

1 Introduction

Due to its versatility, durability and sturdiness concrete is the basic building materials and is at the base of the modern structures [1]. Cement, fine and coarse aggregates and water combine to form concrete, which undergoes a chemical process, called hydration to convert from a fluid state to a stony mass [2]. It is used in buildings, bridges, highways, dams and tunnels for lots of applications because it bears large geodetic stress and if it is poured in a mould, the concrete takes its shape [3-4]. Further extensions have been added in concrete mix design progress as well as extra included additives such as Fly ash (FA), Silica fume (SF), Ground granulated blast furnace slag (GGBFS) and Metakaolin (MK) for improving the mechanical properties and sustainability of concrete [7].

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In order to be able to fulfill the requirements of some projects, new generations of constructions have also produced specialty concrete like fiber reinforced concrete, self-compacting, and high-performance concrete [5-6]. Concrete has a lot of benefits that can be attributed to its uses, but it also has some disadvantages most popular of which is the environmental concerns which is as a result of the huge release of CO_2 emissions during cement production [8]. To overcome this the following sustainable substitutes are under scrutiny namely carbon capture technology, recycled aggregates and mixed cement. The position of concrete as one of the most effective building materials has been made possible by its ability to undertake performance, costs and flexibility. It is a dominant player for development of urbanization and industrial expansion in the world; its applications cover simple housing projects to massive infrastructural development. Concrete is evolving all the time in order to meet modern architectural requirements for construction, and at the same time considering the consequences it has on the environment due to different aspects of sustainability and production enhancements [9-10]. The durability performance of quaternary cementitious concrete mixes including metakaolin, GGBS, and limestone powder was assessed. The study attributed the benefits to the pozzolanic and filling actions of the SCMs and showed greater resistance to acid attacks and chloride ion penetration, especially in harsh conditions [11].

Investigation on the mechanical and durability performance of quaternary blends, optimal proportions of SCMs contribute to sustainable building practices and result in notable improvements in mechanical performance, and resistance to chemical assaults. Some investigated the mechanical behaviour and hydration process of quaternary blended mixtures, highlighting the fact that fly ash and GGBS aid in the creation of long-term strength, whereas metakaolin speeds up early hydration [12]. It was discovered that adding limestone powder enhanced workability and encouraged the development of dense microstructure. Quaternary mixed concrete performs better in challenging environmental circumstances, which supports its use in industrial and maritime constructions. GGBS improves workability and decreases shrinkage while increasing the quaternary blends' long-term compressive strength [6]. Optimized quaternary mixes produce high-performance concrete with exceptional durability, including resistance to ASR, chloride intrusion, and sulfate assault. The potential of quaternary mixed cementitious concrete in contemporary building is highlighted by the examined literature. Metakaolin promotes early strength and microstructural refinement, fly ash adds long-term strength and workability, and GGBS increases durability and decreases permeability [6-8]. When these materials are used together, they provide exceptional fresh and hardened qualities, which makes quaternary blends a high-performance and environmentally friendly option for a variety of building applications.

1.1 Quaternary Blended Concrete (QBC)

QBC is a more refined type of concrete that has four mineral bolstering agents or supplementary cementitious materials (SCMs), water, aggregates and OPC. The common SCMs include FA, SF, GGBFS, and MK or rice husk ash, all of which impart some or the other characteristics to the mixture. All these make the concrete stronger mechanically, more enduring and sustainable when the two are combined. Due to improved chemical attack resistance, reduced permeability, and controlled heat of hydration associated with quaternary blends, these mixes are appropriate for marine structures, bridges, and dams. They use less OPC and recycle industrial waste and therefore they support the environment empowering sustainable living. However, challenges such as mix proportioning, variation in SCM quality, and long setting time require to be addressed. Overall, quaternary mixed concrete is a green and versatile product for long span construction and application with high performance characteristics.

1.2 Supplementary Cementitious Materials (SCMs)

1.2.1 Fly ash (FA)

FA consists of 90% of aluminosilicates that are produced from burning coal in utilities. Usually, it is divided into two categories: Class F andC FA are a by-product of burning bituminous or anthracite coal and is a pozzolanic material which in the presence of water reacts with calcium hydroxide in concrete to enhance its strength and durability. Due to these many benefits FA is commonly used in the production of concrete. FA increases the long-term strength due to its interaction with calcium hydroxide to form more C-S-H, increases workability through increasing the flow ability of the mix, and reduces heat of hydration that aids in reducing cracking in large mass pours. Reducing permeability and increasing resistance to chemical attacks including sulfate and chloride, and protection of steel reinforcement besides also improving the durability of concrete is another advantage of fly ash. Due to its ability to replace partly Portland cement, fly ash is known to reduce emissions of CO_2 as well as make a positive impact towards more sustainable production of concrete. Therefore, in the present study FA has been considered as one of the materials to replace cement in QBC

1.2.2 Ground Granulated Blast Furnace Slag (GGBS)

Steel making generates GGBS which is a high performance SCM. It is made by cooling molten slag: a waste created when making iron and steel, through steam or water, and it results in fine, glassy granules. GGBS, used as a powder material because of pulverization, presents cementitious properties and is used in production of concrete to enhance its sustainability, strength, and sustainability. GGBS lowers the risk of ASR, thus enhances durability of concrete. In addition, it reduces heat of hydration during the curing process and contributes to the protection against thermal cracking in large volume concreting such as foundation and dams. Through the reaction with calcium hydroxide to form more of the C-S-H which is the component that contributes to the strength of concrete, GGBS enables the development of strength from structural point of view in the long run.

1.2.3 Metakaolin (MK)

MK, a thermally altered product of kaolin clay, used in geopolymer synthesis, is purified through calcination at 600 to 800°C. The method of calcination alters the physical and chemical properties of Kaolin for use in diversified applications in the building sector.
MK is prepared by thermally deactivating naturally occurring kaolin clay, which contains silica and alumina. MK is a non-crystalline, highly reactive form of kaolin that is obtained upon calcination of kaolin's SOH at a temperature of between 650°C and 800°C. This material is commonly incorporated into a concrete as a SCM as a way of improving on its strength, and physical characteristics.
For concrete application MK has the following advantages: It enhances the early strength properties of concrete by participating in pozzolanic reactions with a reaction product of cement; calcium hydroxide. Furthermore, this reaction produces extra calcium silicate hydrate (C-S-H), the phase mainly responsible for the strength and porosity of concrete. Besides, through reduction in permeability and porosity of concrete, MK boosts up the

concrete protection against sulfate attack, ASR and chloride ion diffusion. Due to such characteristics, it is suitable for use in construction of structures that experience tough environments including chemical industries and sea structures. In addition, it reduces efflorescence common problem that sees calcium hydroxide moving to the surface of a concrete to provide a better-looking surface.

2. Methodology

2.1 Mix Preparation

Following are different mixes considered for the present study and control mix is used for comparing the strength with different mixes as shown in Table 1.

Table 1. Different Mix

Materials	Mix 1	Mix 2	Mix 3	Mix 4
OPC (%)	100	55	50	45
GGBS (%)	-	10	15	20
FLYASH (%)	-	30	30	30
METAKAOLIN (%)	-	5	5	5

2.2 Sample Preparation

Before the supplementary elements are added, the attributes related to the reference mix are examined. Conventional concrete was created in accordance with the standards outlined in IS 10262 (2009). The design considers a w/c ratio of 0.45. For M65 grade concrete, the target mean strength was 60 MPa. The materials include river sand, 20 mm granite stone, and OPC 53 Grade cement (Ordinary Portland Cement that complies with IS:12269-1987 and has a specified strength for 28 days of at least 53 MPa). The mixture was cast in 150 × 150 × 150 mm cube moulds for the compressive strength test, and the specimens were demoulded 24 h after casting. For the split tensile strength test, cylinders measuring 150 mm in diameter and 300 mm in height were prepared. For the flexural strength test, prisms measuring 150 × 150 × 750 mm were prepared.

3. Results and Discussion

The standard consistency test was conducted to determine the amount of water required to produce a cement paste of standard consistency, and the initial and final setting times were measured. All values were within the limits specified in IS 4031, confirming that the cement was suitable for subsequent testing. The results are presented in Tables 2 and 3.

Table 2. Standard Consistency Test

Mixes	Consistency%
1	32
2	30
3	28
4	28

Table 3. Initial and Final Setting time

Mixes	Initial Setting (Min)	Final Setting (Min)
1	150	220
2	155	240
3	159	258
4	162	280

3.1 Fresh Properties of Mixes

In the workability tests, conventional concrete and QBC at a w/c ratio of 0.45 performed comparably. This indicates that the proposed quaternary blend proportions can produce workable concrete. The slump cone and compaction factor results are presented in Tables 4 and 5.

Table 4. Slump Test

Mixes	Slump Size (Mm)
1	112
2	106
3	100
4	96

Table 5. Compaction Factor Test

Mixes	Compaction Factor
1	0.84
2	0.86
3	0.86
4	0.88

3.2 Hardened Properties of Mixes

3.2.1 Compressive strength

Compressive strength has been considered as the most important parameter in terms of concrete material, in the present study for the QBC with the high grade M65 and w/c ratio of 0.45, following results have been presented. Mix 3 achieved the highest compressive strength, showing a 1.05% increase over the OPC control. The compressive strength values for all mixes are given in Table 6. The test setup is shown in Fig. 1, and the results are plotted in Fig. 2.

Table. 6 Compressive Strength Test

Mixes	Compressive strength (MPa)	
	7 days	**28 days**
1	43.37	70.76
2	46.57	71.83
3	52.06	74.50
4	50.60	73.75

Fig. 1 Testing Sample for Compressive strength in Lab.

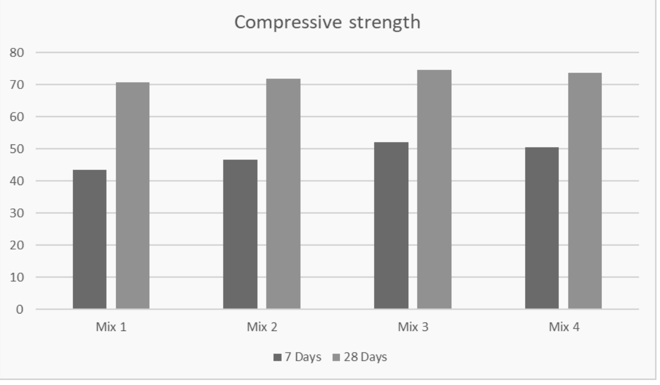

Fig. 2 Compressive strengths values at 7 and 28 days for all mixes.

3.2.2 Flexural Strength

Table 7 presents the flexural strength results for the mixes tested. Flexural strength increased with increasing GGBS content, while the proportions of FA and MK were held constant across the mixes.

Table. 7 Flexural Strength Test

Mixes	Flexural strength (MPa)	
	7 days	28 days
1	1.84	5.84
2	2.36	6.28
3	2.56	6.30
4	2.82	6.34

3.2.3 Split Tensile Strength

Table 8 gives the Split tensile strength results for the different mixes prepared and as per results it can be seen that strength has been increased with increase in GGBS percentage whereas in the mixes ratio of FA and MK has been kept constant

Table. 8 Split Tensile Strength Test

S.No	Mixes	Split Tensile strength (MPa)	
		7 days	28 days
1	1	1.28	4.08
2	2	1.65	4.39
3	3	1.79	4.41
4	4	1.97	4.43

4. Conclusion

Because GGBS has a large surface area and high-water consumption, standard consistency in the quaternary binder (OPC-FA-GGBS-MK) decreased as percentage levels of GGBS increased. These results showed that both water and standard consistency may be handled by regulating the percentage level of GGBS in the mixes. QBC has delay in setting up qualities due to slow hydration. This suggests that as the amount of pozzolanic process increases, so does the time period. In the production of RMC concrete, where a longer placement time is required, these binders are helpful. Workability of CC and QBC looks similar, whereas all Mixes can be considered as the workable concrete. Compressive, flexural and split tensile results also proved that QBC has better strength compared to CC and by using these SCM the main reason was to reduce cement consumption. Even though there was only 1% to 3% of increment in strength parameters, QBC can considered instead of CC to reduce cement content in huge projects as strength parameters proved that QBC can also give same strength. And MK can also be incorporated for the partial replacement in QBC, as there is no reduction of strength in fresh and hardened properties. While considering concrete in terms of Strength, Sustainably and Durability parameters, these SCM are also industrial by products, by utilizing these materials, waste dumping can also be reduced. Therefore, from the present study, it can be considered as a better option for RMC and huge constructions and further studies related to durability properties can also be studied for the present work.

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References

1. Aïtcin, P. High performance concrete. In CRC Press eBooks. (1998). https://doi.org/10.4324/9780203475034
2. Al-Naghi, A. a. A., Ahmad, A., Amin, M. N., Algassem, O., & Alnawmasi, N. Sustainable Optimisation of GGBS-Based Concrete: De-Risking Mix Design through Predictive Machine Learning Models. Case Studies in Construction Materials, 23, **e04900**. (2025). https://doi.org/10.1016/j.cscm.2025.e04900
3. Babu, G. K., Rao, K. V., Dey, S., & Veerendra, G. Performance studies on quaternary blended Geopolymer concrete. Hybrid Advances, 2, **100019**. (2023). https://doi.org/10.1016/j.hybadv.2023.100019
4. Dave, N., Misra, A. K., Srivastava, A., & Kaushik, S. K. Experimental analysis of strength and durability properties of quaternary cement binder and mortar. Construction and Building Materials, ***107***, **117–124**. (2016). https://doi.org/10.1016/j.conbuildmat.2015.12.195
5. Kumar, R., Tomar, P., Srivastava, A., Lakhani, R., & Chibber, V. K. Improvement of Mechanical and Microstructure Properties of Modified Fly Ash-Blended Low Carbon Cement with Hydroxy Propyl Methyl Cellulose Polymer. *Iranian Journal of Science and Technology Transactions of Civil Engineering*, *46*(6), **4219–4232**. (2022). https://doi.org/10.1007/s40996-022-00855-4
6. Ningampalli, R., Rao, M. V. S., & Desai, V. B. (2024). Flexural and cracking behavior of reinforced lightweight self-compacting concrete beams made with LECA aggregate. Journal of Sustainable Construction Materials and Technologies, 9(2), **159–169**. https://doi.org/10.47481/jscmt.1500907
7. Penki, R., Jogiparthi, S., Kaushiki, M., & Kona, M. (2024). Conceptual integration of transparent concrete with other forms of concrete to develop a holistic sustainable green material: Energy saving. *Indian Journal of Environmental Protection, 44*(1), 24–37. https://www.researchgate.net/publication/393495398
8. Sata, V., Jaturapitakkul, C., & Kiattikomol, K. Influence of pozzolan from various by-product materials on mechanical properties of high-strength concrete. Construction and Building Materials, 21(7), **1589–1598.** (2006). https://doi.org/10.1016/j.conbuildmat.2005.09.011
9. Siddique, R., & Klaus, J. Influence of metakaolin on the properties of mortar and concrete: A review. Applied Clay Science, 43(3–4), **392–400.** (2008). https://doi.org/10.1016/j.clay.2008.11.007
10. Yang, Y., Liu, T., and Shi, J. Durability performance of quaternary cementitious systems incorporating metakaolin and limestone powder, Cement and Concrete Composites, 122, pp. **104–111** (2021),
11. Zhang, Y., Zhang, Q., AlAteah, A. H., Essam, A., & Mostafa, S. A. Predictive Modeling for Mechanical Characteristics of Ultra High-Performance Concrete Blended with eggshell powder and nano silica Utilizing Traditional Technique and Machine Learning Algorithm. Case Studies in Construction Materials, **e04025.** (2024). https://doi.org/10.1016/j.cscm.2024.e04025
12. Scholer, A., Lothenbach, B., Winnefeld, F., & Zajac, M. Hydration of quaternary Portland cement blends containing blast-furnace slag, siliceous fly ash and limestone powder. Cement and Concrete Composites, *55*, **374-382**. (2015). https://doi.org/10.1016/j.cemconcomp.2014.10.001