Experimental Study on Optimised Design And Performance Analysis of Pavement Quality Concrete

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Abstract- *This study examines the combined influence of Fly Ash (FA), Vitrified Polish Waste (VPW), and Ground Granulated Blast Furnace Slag (GGBFS) as supplementary cementitious materials (SCMs) in M40 grade Pavement Quality Concrete (PQC). Cement was partially replaced in incremental proportions of 5%, 10%, 15%, and 20% using blended combinations of FA and GGBFS along with a fixed 15% VPW content. All mixes were designed with a constant water-to-binder ratio of 0.34 following IRC:44-2017 guidelines. Mechanical performance was evaluated through compressive strength, split tensile strength, and flexural strength at 7 and 28 days. Results indicate that mechanical strength steadily increased with SCM content up to an optimum replacement of 15%, beyond which performance declined. The optimum mix exhibited superior compressive, tensile, and flexural behavior compared to conventional M40 PQC. This study demonstrates that incorporating industrial waste materials such as FA, GGBFS, and VPW enhances performance while promoting sustainable and cost-effective pavement construction.*

Keywords- Fly Ash, GGBFS, Vitrified Polish Waste, Pavement Quality Concrete, Mechanical Properties

I. INTRODUCTION

Concrete remains the most widely used construction material for infrastructure development, particularly in rigid pavements where long-term strength and durability are essential. Pavement Quality Concrete (PQC), typically designed using M40 grade concrete, plays a critical role in supporting heavy traffic loads, resisting environmental degradation, and ensuring long service life with minimal maintenance. However, conventional PQC relies heavily on Ordinary Portland Cement (OPC), the production of which is energy-intensive and contributes substantially to global carbon dioxide emissions. With the growing emphasis on sustainable construction practices, there is an increasing need to explore environmentally responsible alternatives that reduce cement consumption without compromising performance.

Industrial by-products such as Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBFS), and Vitrified Polish Waste (VPW) have emerged as effective supplementary cementitious materials (SCMs) capable of enhancing concrete properties while addressing issues related to industrial waste disposal. Fly Ash, a by-product of coal combustion, improves long-term strength and workability due to its pozzolanic characteristics. GGBFS, derived from iron-making slag, offers improved durability, reduced heat of hydration, and enhanced long-term performance. Similarly, VPW, generated in large quantities by the ceramic manufacturing industry, possesses cementitious potential due to its high silica and alumina content. Utilizing these wastes in concrete not only reduces environmental impact but also supports sustainable material management.

Although SCMs are extensively studied in building construction, their application in PQC remains limited, particularly in optimized blended forms. Since pavements demand high flexural strength, abrasion resistance, and durability, evaluating the combined effects of FA, GGBFS, and VPW becomes essential for developing high-performance, eco-friendly pavement materials. Previous studies indicate that incorporating ceramic waste and GGBFS can improve mechanical properties and durability, while fly ash contributes to enhanced microstructure and reduced permeability. However, the optimum replacement levels and performance characteristics in M40 PQC require further investigation.

This study focuses on assessing the mechanical behavior of M40-grade pavement concrete by partially replacing cement with blended proportions of FA, GGBFS, and VPW. The research aims to identify the optimal replacement percentage that maximizes compressive, flexural, and split tensile strengths while maintaining desirable workability. By integrating multiple industrial by-products, the study promotes sustainable pavement construction and contributes to reducing cement consumption, lowering carbon emissions, and minimizing waste disposal challenges.

PROPERTIES OF CONCRETE
A hardened concrete must possess the following properties,

- Strength
- Durability
- Workability

- Shrink agen & Creep

I. Strength

Strength is defined as the opposite reaction of the hardened concrete to rupture at different loading conditions and accordingly different tests are conducted to compressive strength, split-tensile strength, flexural strength, etc. The increase of strength depends upon grade, type of cement, curing and environmental conditions.

II. Durability

A durable concrete is one that performs efficiently in the working environment during its probable exposure conditions during the service. The main characteristic that influences the long life of concrete is the permeability to entering of water, harmful gases like sulphates, oxygen, chloride, carbon dioxide etc.

III. Workability

Workability of concrete is the characteristic of concrete which is used to find the amount of internal work, which is necessary to produce the condition of full compaction. The biggest unique factor affecting the workability is the quantity of water content which is present in the mix.

IV. Shrinkage

Shrinkage is defined as the change of volume of concrete due to thermal properties of aggregates and the environmental conditions. The total amount of moisture content present in the concrete at the time of mixing mostly influences the total shrinkage of concrete and to a lesser extent, by the cement content.

Creep

The time dependent division of strain affecting due to stress in concrete is known as creep. It depends upon duration of loading, mix proportions and influence of aggregates.

Segregation and Bleeding

Segregation can be termed as the process of dissociation of the constituent materials which are present in concrete. A good concrete is the concrete in which all the materials are thoroughly and evenly distributed to make an even mixture. Bleeding in concrete is termed as gaining of water. It is a particular form of segregation, in which. Some of the water content from the concrete extracts out to the surface of the concrete, which have the lowest specific gravity amongst all the materials of concrete. Bleeding is comparatively observed in mostly wet mix, ill proportioned and unevenly mixed concrete

II. LITERATURE REVIEW

Lilesh Gautam et al. [2021] [3] The review by Lilesh Gautam et al. explores the potential of ceramic waste as a sustainable substitute in concrete production. With the construction industry's increasing demand for raw materials and the environmental impacts of cement manufacturing, ceramic waste offers a promising alternative due to its rich content of silica and alumina, which exhibit pozzolanic activity. The study highlights how ceramic waste can partially or fully replace cement, fine or coarse aggregates, and act as a filler in concrete, mortar, and self- compacting concrete (SCC). The review confirms that ceramic waste contributes to better workability retention, lower chloride ion permeability, and enhanced long- term strength. Overall, ceramic waste supports environmental sustainability and efficient waste management in the construction industry

Moatasim Attaelmanan Alnour et al. [2021] [4] The study demonstrates the potential of ceramic waste powder (CWP) as a sustainable and economical partial replacement for cement in concrete production. Experimental results indicate that replacing cement with CWP in the range of 5–20% can yield comparable or improved mechanical properties, particularly at a 5–10% replacement level, which showed the highest compressive and tensile strength improvements at 28 days. Although early strength development is generally slower due to the pozzolanic nature of CWP, the long-term performance is enhanced due to improved microstructure, reduced porosity, and better durability characteristics. Higher replacement levels (above 20%) tend to reduce compressive strength but still offer satisfactory performance for non-structural or durability-prioritized applications. Overall, the research supports the integration of CWP into concrete as a viable alternative to ordinary Portland cement, reducing environmental burden from ceramic waste disposal and CO_2 emissions from cement production. CWP-blended concrete contributes positively to sustainable construction without significantly compromising strength or durability.

L. H. Pereira Silva et al. [2023] [12] This study focuses on the application of blast furnace slag (BFS) in concrete pavement to reduce the environmental impact of Portland cement manufacturing. A systematic literature review was conducted to analyze recent scientific literature on the use of BFS in pavements. The review identified 20 articles published in the last five years that discussed the effects of BFS on mechanical properties, chemical composition, and physical properties of concrete. The results highlight the potential benefits of using BFS in concrete pavement applications, including improved durability, freeze-thaw resistance, and cost savings.

S Sathvik et al. [2025] [13] This study successfully demonstrated the potential of fly ash and manufactured sand (M sand) as sustainable alternatives to Ordinary Portland Cement (OPC) and river sand in M40-grade concrete. Experimental results revealed that a 25% replacement of OPC with fly ash and 50% replacement of river sand with M sand achieved the target compressive strength after 28 days. Machine learning models, particularly XGBoost, provided highly accurate predictions for compressive strength, outperforming other models. SEM-EDS analysis confirmed the development of compact microstructures with favorable elemental compositions. These findings support eco-friendly concrete production while ensuring structural performance and reducing environmental impact.

S.S. Vivek & G. Dhinakaran [2017] [15] Self Compacting Concrete (SSC) has revolutionized the construction industry with its innovative properties. This study explores the optimal ratios of mineral and chemical admixtures to develop SCC with a compressive strength of 60 MPa. GGBFS, SF, and MK were used as partial substitutes for cement in varying proportions. Fresh and hardened properties of the three types of SCC were investigated, highlighting the significance of GGBFS (50%), SF (10%), and MK (20%) as ideal replacements. The findings emphasize the importance of fresh properties in achieving workability and strength in SCC, paving the way for environmentally friendly concrete production.

M S Islam [2015] [16] This study highlights the potential of fly-ash as a sustainable supplementary cementitious material in concrete production. Replacing cement with fly-ash up to an optimum level of 30% significantly enhances the long-term strength and durability of concrete, reducing permeability and chloride ion penetration due to the pozzolanic reaction that forms additional calcium silicate hydrate (C-S-H) gel. These improvements contribute to reduced corrosion risk in embedded steel reinforcement and promote sustainability by lowering CO_2 emissions and the consumption of virgin materials. Thus, fly-ash blended concrete presents a viable, eco-friendly alternative for durable construction in aggressive environments.

M Jamshid et al. [2025] [17] Concrete pavement performance is influenced by multiple factors, including temperature, construction practices, and mixture composition. Pavement distress often results from a combination of factors rather than fatigue failure alone. To improve performance, a multifaceted approach is necessary, considering design, materials, and construction practices. Recommendations include optimized design, high-quality materials, and careful construction to ensure long-lasting concrete pavements.

Hancheng Dan et al. [2021] [18] The Journal of Traffic and Transportation Engineering published a review paper in 2021 on advancements in pavement engineering. The paper highlights innovations in pavement materials and engineering. It analyses five key areas, including asphalt binder and mixture performance. The review provides valuable insights into the latest developments in pavement engineering research

H. Khazaei et al. [2020] [19] The study explores the Combined Graphical Method (CGM) for optimizing concrete mix design, focusing on aggregate properties examining factors like combined gradation, maximum density, retained percentage, air voids, and density. The method is suitable for concrete pavement mix, determining the C/F ratio of coarse and fine aggregates. The study also examines compressive and flexural strength at different curing ages.

Ashlesha Deshmukh et al. [2017] [20] This study explores the design of rigid pavements using Chi-Square hypothesis to analyse factors like deflection, truck speed, and the effect of steel fibres on compressive and flexural strength. It also examines the use of eco-friendly materials such as fly ash and UFS in M-20 concrete mixes, as well as the relationship between recycled aggregates and pavement thickness. The research highlights cost benefits and the importance of considering new materials for sustainable pavement construction. Proper design ensures economic and long-lasting pavement performance

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Noor Azlina Abdul Hamid et al. [2021] [11] This review highlights the potential of Ground Granulated Blast Furnace Slag (GGBS) as a sustainable partial replacement for cement in concrete. Derived from steel industry waste, GGBS possesses cementitious properties due to its high calcium silicate and aluminosilicate content. When used in proportions of 30% to 60%, GGBS enhances concrete's workability, durability, and long-term compressive strength while reducing the rate of hydration and CO_2 emissions. Though early-age strength is lower, strength significantly increases after 28 to 90 days. The study concludes that GGBS is effective in producing environmentally friendly and structurally sound concrete mixtures

M.T.S Lakshmayya et al. [8] [2017] Waste This study focuses on enhancing the mechanical performance and cost-efficiency of rigid pavements by incorporating Vitrified Polish Waste (VPW) into M40 grade concrete. VPW, a ceramic industry byproduct, is used as a partial cement replacement to improve sustainability and reduce construction costs. Various mix proportions were tested, with 15% VPW identified as the optimum replacement level, yielding improved compressive, flexural, and split tensile strengths. Durability tests showed marginal strength reduction under acidic conditions but within permissible limits. The mix design adhered to IS codes and included comprehensive testing of workability, strength, and durability. A cost- benefit analysis demonstrated the economic viability of using VPW making the modified rigid pavement a sustainable and durable alternative to traditional concrete pavements in road infrastructure

Procedure:

1. Material Collection and Preliminary Testing

All materials required for the experimental program—Ordinary Portland Cement (OPC 53 grade), fine aggregates, coarse aggregates, Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBFS), and Vitrified Polish Waste (VPW)—were collected and tested as per relevant IS codes.

- Cement tests were performed according to IS 4031.
- Fine and coarse aggregates were examined following IS 2386 for grading, specific gravity, and water absorption.
- VPW, FA, and GGBFS were tested for fineness and specific gravity as per IS 4031 and IS 1727.

2. Mix Design for M40 Grade Concrete

The concrete mix was designed according to IRC:44–2017, targeting a flexural strength-based design suitable for Pavement Quality Concrete (PQC).

- Water–cement ratio was fixed at 0.34.
- Mix proportion was finalized as 1 :1.59 : 3.387 (cement : fine aggregate : coarse aggregate).
- Slump target for PQC was maintained between 25–50 mm.
- Superplasticizer was incorporated to achieve the required workability.

3. Preparation of Blended Cementitious Mixes

Cement was partially replaced using blended combinations of FA, GGBFS, and VPW. The replacement levels used were:

- 5%, 10%, 15%, and 20% (Fly Ash + GGBFS)
- VPW fixed at 15% for all replacement mixes

Five different mixes were prepared, including a control mix with 0% SCMs.

4. Mixing Procedure

Concrete was mixed in a batch mixer following a controlled sequence:

1. Add coarse aggregate into the mixer.
2. Add fine aggregate and dry-mix thoroughly.
3. Introduce cement, VPW, FA, and GGBFS and continue mixing.
4. Add water mixed with superplasticizer gradually.
5. Continue mixing for 5 minutes to ensure uniformity. Special attention was given to achieve homogeneous blending of VPW and GGBFS, indicated by uniform color distribution.

5. Casting of Specimens

Fresh concrete was placed into lubricated molds in three layers and compacted using a tamping rod. Specimens prepared:

- Cubes (150 × 150 × 150 mm) – for compressive strength
- Cylinders (150 mm × 300 mm) – for split tensile strength
- Prisms (500 × 100 × 100 mm) – for flexural strength

Vibration was applied to remove entrapped air, and the surface was leveled.

6. Curing of Specimens

After 24 hours of initial setting, specimens were removed from molds and placed in a curing tank. Curing was done for:

- 7 days
- 28days
  as per IS 516–1959 requirements.

Table 1 – Properties of Cement

Test	Result	Code Used	Standard Range
Specific Gravity	3.16	IS 4031 (Part 9):1988	3.0 – 3.20
Fineness (% retained, 90 µm)	5.5%	IS 4031 (Part 1):1988	<10%
Normal Consistency	30%	IS 4031 (Part 4):1988	27 – 33%
Initial Setting Time	60 min	IS 4031 (Part 4):1988	>30 min
Final Setting Time	480 min	IS 4031 (Part 5):1988	<10 hours
Soundness	2 mm	IS 4031 (Part 3):1988	<2 mm

Table 2 – Properties of Fine Aggregate

Test	Result	Code Used	Standard Range	Test
Specific Gravity	2.68	IS 2386 (Part 3):1963	2.5 – 3.0	Specific Gravity
Fineness Modulus	2.60	IS 2386 (Part 1):1963	2.2 – 2.6	Fineness Modulus
Water Absorption	1%	IS 2386 (Part 3):1963	0.1 – 2%	Water Absorption
Grading	Zone II	IS 383:1970	Conforming	Grading

Table 3 – Properties of Coarse Aggregate

Test	Result	Code Used	Standard Limit	Test
Specific Gravity	2.64	IS 2386 (Part 3):1963	2.5 – 3.0	Specific Gravity
Crushing Value	18.6%	IS 2386 (Part 4):1963	< 30%	Crushing Value
Impact Value	24.6%	IS 2386 (Part 4):1963	< 35%	Impact Value
Flakiness Index	8.42%	IS 2386 (Part 1):1963	< 15%	Flakiness Index

Table 4 - Properties of Vitrified Polish Waste (VPW)

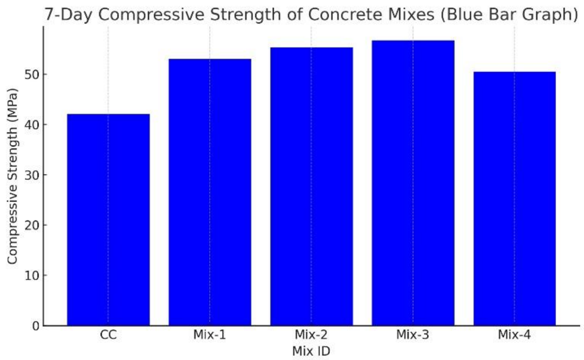
Test	Result	Code Used
Test	**Result**	**Code Used**
Specific Gravity	2.45	IS 4031 (Part 11):1988

Table 5 – Properties of GGBFS

MixID	FlyAsh (%)	MassLoss(%) after 28 days
Test	**Result**	**Code Used**
Specific Gravity	2.45	IS 4031 (Part 11):1988

CONCLUSION FROM TEST RESULTS

- **The 15% replacement of cement with Fly Ash and GGBFS (with 15% VPW constant)** achieved the **highest compressive, split tensile, and flexural strengths**, outperforming the control mix.
- **Strength increased steadily from 5% to 15% replacement, showing improved cementitious reactions and better microstructure development.**
- **At 20% replacement**, all strength values decreased, indicating that higher replacement reduces bonding and weakens the concrete matrix**.**
- Overall, the **15% replacement level** is identified as the **optimum mix** for achieving maximum mechanical performance in M40 grade Pavement Quality Concrete..



III. CONCLUSIONS

The results obtained from compressive strength, split tensile strength, and flexural strength tests clearly indicate that the mechanical performance of M40 grade Pavement Quality Concrete improves with the inclusion of Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBFS), and Vitrified Polish Waste (VPW) up to an optimum replacement level. Among all mixes, the **15% combined replacement of FA + GGBFS with a constant 15% VPW** achieved the highest strength values at both **7 days and 28 days**, outperforming the control mix.

The compressive strength increased gradually from 5% to 15% replacement, confirming enhanced cementitious activity and improved bonding due to the synergistic effects of FA, GGBFS, and VPW. Similarly, split tensile and flexural strengths followed the same trend, showing maximum improvement at 15% replacement. These gains confirm better microstructural development and improved load transfer capacity in the optimized mix.

However, when the cement replacement increased beyond 15%, all strength parameters showed a reduction. This decline can be attributed to insufficient cement content and lower early-age reactivity of the supplementary materials, which reduced the overall binding efficiency of the concrete matrix.

Based on the test results, it is concluded that **15% replacement of cement with FA and GGBFS (with 15% VPW)** provides the best balance of strength and performance. This mix satisfies PQC strength requirements and delivers superior mechanical properties compared to the control mix, making it the **most suitable and performance-efficient blend for pavement applications.**

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