RESEARCH ARTICLE OPEN ACCESS

# Assessment of Strength and Durability of M70 Grade Quaternary Blended Concrete Manufactured Using SCMs

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**Abstract:**
This research addresses the dual imperatives of durability and sustainability in modern construction by exploring the use of Supplementary Cementitious Materials (SCMs) to partially replace Ordinary Portland Cement (OPC) in concrete mixes. The study aimed to achieve three key objectives: improving economic feasibility, enhancing sustainability, and optimizing concrete performance. Various SCMs such as fly ash, ground granulated blast furnace slag (GGBS), and micro silica were blended to create quaternary concrete mixes (TM2, TM3, TM4, and TM5), which underwent comprehensive laboratory testing. Tests included assessments of compressive strength, water permeability, Rapid Chloride Penetration Test (RCPT), Rapid Chloride Migration Test (RCMT), and electrical resistivity. Results demonstrated that SCM-based concretes exhibit superior strength, enhanced durability, and improved microstructure compared to traditional OPC concrete. TM4, notably with 25% GGBS replacement, showed optimal performance, meeting stringent standards for water permeability at 28 and 56 days. RCPT and RCMT results confirmed reduced chloride ion penetration across all mixes, with TM4 exhibiting the lowest rates. Electrical resistivity tests highlighted TM3 and TM5 as top performers, surpassing industry durability benchmarks. The study advocates for widespread adoption of SCM-blended concretes in construction, citing their economic benefits and positive environmental impact.
**Keywords:** Strength, durability, blended concrete, water permeability, Supplementary cementitious materials, chloride penetration.

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Date of Submission: 12-06-2024 Date of acceptance: 24-06-2024

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## I. Introduction

Cement was found about 200 years ago however it is still popular and most frequently used construction material worldwide [1]. Increased carbon footprint is a major cause of concern in the construction industry [2]. Hence people started experimenting use of various supplementary cementitious materials (SCM) in concrete as a partial replacement for cement [3]. This helps to reduce the clinker content per $m^3$ of concrete. Additions of these latent hydraulic and pozzolanic binders as partial replacement of cement contribute differing levels of effect on rheology, and long-term properties of concrete [4]. It improves strength and impermeability leading to much better performance of concrete. SCM blended concrete has better fire resistance and greater corrosion resistance [5]. Hence researchers are further trying to increase the cement replacement with the help of innovative chemical admixtures as water reducers and mineral admixtures i.e. various SCMs like fly ash, silica fume, GGBS, etc [6].

The use of fly ash generated in thermal power plants reduces the consumption of natural resources and helps protect the environment [7]. The studies conducted by many researchers show that the use of fly ash as a cementitious material makes concrete economical and durable [8]. Components of the fly ash produced vary depending upon the source of the coal being burned but all type of fly ash includes silica (silicon dioxide, $SiO_2$) and lime (calcium oxide, CaO). In recent years fly ash has been commonly used to supplement Portland cement in concrete production. Fly-ash particles are spherical and their shape allows for making free-flowing concrete. This property of fly ash makes it a desirable admixture in concrete.

The major types of SCM are by-products from industrial processes such as fly ash from coal-fired power stations, ground granulated blast furnace slag (GGBS) from steel-making industries, micro silica from ferrosilicon production industries, and metakaolin from clay refining stations. When GGBS is added to concrete improves the durability of the concrete [9]. This improvement is because of delayed hydraulicity due to the very slow formation of C-S-H and reaction with portlandite to form additional C-S-H that helps pore refinement with time. Micro silica having a relatively small particle size compared to concrete particles becomes useful to fill small pores. A small addition of it helps to improve the mechanical properties as well as the durability. They have a high surface area making them highly reactive. The particles of silica react with $Ca(OH)_2$ and form additional C-S-H gel. Both these properties of microsilica enhance the concrete performance in the long run. A study by Yu et al. showed that the replacement of cement by 3.7 % microsilica optimally increased both flexural and compressive strength. However, the lower amount of replacement of cement by microsilica showed a denser microstructure. [10].

High-strength and high-performance concrete are commonly used throughout the world and to produce higher strengths it is necessary to reduce the water/cement ratio and increase the binder content. The workability of these concretes is achieved by adding superplasticizers. In addition to it, different kinds of cement replacement materials are added to them to get desired outcomes such as low porosity and low permeability. Especially mineral admixtures like GGBS, fly ash, and silica fume are commonly used to improve the interface with the aggregate. The cracking of high-performance concrete is a big concern for researchers because harmful materials can penetrate through the cracks into the concrete easily and destroy reinforcement [11], [12]. Chloride-induced corrosion by chlorine ions is having a major impact on reinforced concrete structures constructed in coastal areas. Corrosion damage to such structures is often visible through expansion of reinforcement bars, surface cracking, and detachment of the concrete cover due to the corrosion, etc [13], [14].

## II. Literature survey

According to reports only 30-60% of fly ash is used for some purpose in different countries. Attempts are made to use fly ash in developing blended concrete. The world’s two largest fly ash production countries are China and India [15]. Disposal of it has become an environmental problem as a major quantity of fly ash is landfilled. It is a waste material and industrial by-product available chiefly [16].

Fly Ash is one of the significant industrial waste materials used as SCM in concrete because of its cementitious properties and chemical composition. It is available in bulk quantity in the form of coal-fired ash from power-generating thermal plants and other coal-based industries. Fly ash when blended in concrete exhibits properties like reduced bleeding and cracking at an early age, lower evolution of heat, long-term strength gains, and lower water necessitated for the same workability. Fly ash permits normal replacement in the range of 20-40 % with a high calcium content. Many researchers after experimental studies recommend replacement levels of up to 30%, for applications like driveways, roads, and parking lots cements placed by fly ash up to 70% [17]. It is suited for mass concrete construction as it generates less heat of hydration. Fly ash contains SiO2, $Al_2O_3$, and $Fe_2O_3$ when reacts with calcium hydroxide it forms a C-S-H gel, which acts as a good filler with, augmented strength, corrosion resistance, and reduced permeability.

Pulverized Fly Ash (PFA) is produced as a residue when pulverized coal is burnt at high temperatures. Chemical activators are used in concrete if the fly ash exceeds 80% of cement replacement. Its use in optimum proportion improves concrete performance in fresh and hardened states. Fly ash when used in concrete reduces water requirement and improves the paste flow behavior.

A process of quenching molten iron slag from a blast furnace in water or steam that is then dried and ground into a fine powder derives GGBS. The use of GGBS in cement usually improves workability and decreases the water demand due to the increase in paste volume. In earlier times it was considered useless but now it is used for environmental applications, agriculture, and construction industries.GGBS when used as a partial replacement for cement becomes a sustainable building material for pipes, pavements, foundations as well as for marine structures [18].

Its chemical composition varies depending on the raw materials composition. The compressive and flexural strength of concrete is found enhanced when it is used in concrete. The low-density property of expanded slag permits better mechanical binding with hydraulic cement paste. It is used as an absorbent because of its particle size, surface area, bulk density, apparent porosity, and water-holding capacity.

Micro silica is also known as Silica fume. It is an ultrafine powder collected as a by-product of the silicon and ferrosilicon alloy production industries. This ultra-fine powder contains greater than 85 to 90% silica. Its particles are spherical with an average diameter of 150 mm which is smaller than OPC particles. This is mainly used in high-performance concrete [19].

It was landfilled in the past. Nowadays it is found very significant to be used as a mineral admixture and filler in concrete. When used in quantities ranging from 1 to 2% solid by weight of cementitious materials, they produce a powerful dispersing effect on the cement paste, which can be short-lived [20]. It improves the compressive strength, abrasion resistance, and bond strength of concrete when used with OPC. When silica fume reacts with free Ca(OH) 2 of fresh concrete, it enhances the strength of concrete by making additional C-S-H gel. [21]. This decreases the water permeability and pore structure. In an aggressive environment, it helps resist sulfate attack [22].

Micro silica particle has a diameter 100 times smaller than anhydrous Portland cement particles. The advantages of using it as a replacement for cement are increases in tensile strength, compressive strength, flexural modulus, and tensile ductility, but decrease in compressive ductility, freeze-thaw durability, abrasion resistance, chemical attack resistance, the corrosion resistance of reinforcing steel and bond strength with steel reinforcement [23]. In addition, it also decreases the drying shrinkage, alkali-silica reactivity, creep, permeability, and coefficient of thermal expansion [24].

## III. Materials and Methodology

M70 grade concrete is a high-grade concrete that is very sensitive to changes in the finer-sized particles. Hence single batch of fine aggregates is used in the manufacturing of high-grade concrete. The PFA used is strictly checked and ensured that it is below 16% retention. The same grade of cement is used throughout the test batches. GGBS and Micro silica are used for all trials from the same lot. It is assumed that coarse aggregates used are nominally consistent and have the same properties.

Concrete made by blending supplementary cementation materials like fly ash, GGBS, and micro silica as a partial replacement of cement is said to have become green concrete as it has less carbon emission and the energy required is less for cement production. This section describes the materials used in the blending of concrete and the tests performed in the measurement of durability parameters.

The durability of structure in technical terms is its ability to last long without significant deterioration. To study the durability performance of quaternary blended concrete, the Water Permeability Test (WPT), Rapid Chloride Permeability Test (RCPT), Rapid Chloride Migration Test (RCMT), and Electrical Resistivity Test (ERT) are conducted in the laboratory.

The use of fly ash, a waste material from thermal power plants as a partial replacement for OPC is found suitable for manufacturing durable concrete [26]. In the study of the durability parameters of concrete, it becomes important to investigate the nature of chemical attacks on concrete, loss of weight of concrete, cracking of concrete, etc [27]. OPC has poor resistance to acid attack. However, if fly ash is added to OPC; the microstructural properties of concrete like porosity, permeability, etc. improve [28].

The work presented in this research study is based on quaternary blended cement. It is a new approach in the field of concrete and not practiced in the construction industry in India. IS 456-2000 [29] permits the use of OPC, PSC, PPC, and other cement as per Indian standards.

### 3.1 Materials for M70 grade concrete

Ordinary Portland Cement (OPC), Ambuja Cement-OPC 53 Grade is used. Cement used conforming to IS: 269-2015, Table 2, Clause 6.1. The test report on the chemical analysis of cement is shown in Table 1.

**Table 1: Laboratory test report of chemical analysis of cement**

| Sr. No. | Test Conducted | Result % | Requirement as per IS:269-2015, Table-2, Clause 6.1 |
|---|---|---|---|
| 1 | Loss On Ignition (LOI) | 2.7 | 4.0% Max. |
| 2 | Insoluble Residue (IR) | 2.78 | 5.0% Max. |
| 3 | Sulfur trioxide ($SO_3$) | 2.47 | 3.5% Max. |
| 4 | Silicon dioxide ($SiO_2$) | 21.14 | ------- |
| 5 | Aluminum Oxide ($Al_2O_3$) | 5.48 | ------- |
| 6 | Ferric Oxide ( $Fe_2O_3$) | 4.11 | ------- |
| 7 | Calcium Oxide (CaO) | 60.79 | ------- |
| 8 | Magnesium Oxide (MgO) | 1.60 | 6.0% Max. |

| | | | |
|---|---|---|---|
| 9 | Available Alkali ($Na_2O$) | 0.49 | ------- |
| 10 | Chloride (Cl) | 0.004 | 0.1 % Max. |

### 3.1.2 Fine Aggregate

Crushed sand in the range of 150 microns to 4.75 mm is used in this test program. The same batch of fine aggregates is used in all concrete mixes throughout. The bulk density is 1.74 and the specific gravity in the saturated surface-dry (SSD) state is 2.9. The water absorption of the crushed sand sample is 3.09%. The fine aggregate particle size distribution is shown in Table 2.

**Table 2: Laboratory test report of Fine Aggregate**

| Sr. No. | Test Conducted | Result % | Requirement as per IS:383-2016 |
|---|---|---|---|
| 1 | Bulk Density –Loose (Kg/L) | 1.74 | - |
| | Rodded (Kg/L) | 1.91 | - |
| 2 | Specific gravity –SSD basis | 2.76 | - |
| 3 | Water Absorption (%) | 3.09 | - |
| 4 | Material Finer than 75 microns (%) | 14.4 | 15% for Crushed Stone Sand |

| 1 | Sieve Analysis | % Passing | Zone I | Zone II |
|---|---|---|---|---|
| | 10 mm | 100 | 100 | 100 |
| | 4.75 mm | 100 | 90-100 | 90-100 |
| | 2.36 mm | 72.8 | 60-95 | 75-100 |
| | 1.18 mm | 57.0 | 30-70 | 55-90 |
| | 600 microns | 32.6 | 15-34 | 35-59 |
| | 300 micron | 26.2 | 5-20 | 8-30 |
| | 150 micron | 16.6 | 0-10 | 0-10 |

### 3.1.3 Coarse Aggregate

Two types of coarse aggregate (CA) in the range of 4.75 -10mm (CA1) and 10-20 mm (CA2) are used in this test program. The same batch of course aggregates is used in all concrete mixes throughout.

**Table 3: Laboratory test report of Coarse Aggregate-1**

| Sr. No. | Test Conducted | Result % | Requirement as per IS:383-2016 |
|---|---|---|---|
| 1 | Bulk Density –Loose (Kg/L) | 1.59 | - |
| | Rodded (Kg/L) | 1.69 | - |
| 2 | Specific gravity –SSD basis | 2.97 | - |
| 3 | Water Absorption (%) | 1.32 | - |
| 4 | Flakiness Index (%) | 4.0 | |
| 5 | Elongation Index (%) | 6.0 | |
| 6 | Material Finer than 75 microns (%) | 14.4 | 15% for Crushed Stone Sand |

| | | | |
|---|---|---|---|
| 7 | Aggregate Crushing Value (%) | 10.9 | 30% max for wearing surface. 45% max. for non-wearing surface |
| 8 | Sieve Analysis | % Passing | |
| | 12.5 mm | 99.5 | 100 |
| | 10 mm | 90.3 | 85-100 |
| | 4.75 mm | 1.4 | 0-20 |
| | 2.36 mm | 0.1 | 0.1 |

The bulk density of CA1 is 1.59 and CA2 is 1.67 and specific gravity in the saturated surface-dry (SSD) state is 2.97 and 2.90 respectively. The water absorption of CA samples is 1.32 and 1.11% respectively. The particle size distribution of CA1 and CA2 is shown in Table 3 and Table 4 respectively.

**Table 4: Laboratory test report of Coarse Aggregate-2**

| Sr. No. | Test Conducted | Result % | Requirement as per IS:383-2016 |
|---|---|---|---|
| 1 | Bulk Density –Loose (Kg/L) | 1.67 | - |
| | Rodded (Kg/L) | 1.75 | - |
| 2 | Specific gravity –SSD basis | 2.90 | - |
| 3 | Water Absorption (%) | 1.11 | - |
| 4 | Flakiness Index (%) | 6.9 | |
| 5 | Elongation Index (%) | 8.0 | |
| 6 | Material Finer than 75 microns (%) | 6.7 | 45% max for non-wearing surface |
| 7 | Aggregate Crushing Value (%) | --- | 30% max for wearing surface. |
| 8 | Sieve Analysis | % Passing | |
| | 40 mm | 100 | 100 |
| | 20 mm | 96.2 | 85-100 |
| | 10 mm | 2.8 | 0-20 |
| | 4.75 mm | 0.3 | 0-5 |

**3.1.3 Water**

The quality of water used in the production of high-grade concrete in Ready-Mix Concrete (RMC) plants is a critical factor potable water from a reliable municipal supply is used having a pH value in the range of 6 to 8. This ensured a baseline quality standard and reduced the risk of introducing harmful substances into the concrete mix.

**Table 5: Laboratory test report of PFA**

| Sr. No. | Test Conducted | Result % | Requirement as per IS:3812:2013/ RA:2017 | |
|---|---|---|---|---|
| | | | Part 1 | Part 2 |
| 1 | Specific Gravity(gm/cc) | 2.23 | Not Specified | --- |
| 2 | Fineness Specific Surface in | 334 | 320 | 200 |

| | | | | |
|---|---|---|---|---|
| | $m^2$/kg by Blaine Air Permeability method (Min.) | | | |
| 3 | Lime Reactivity, Average Compressive Strength in N/mm$^2$ (Min.) | 4.6 | 4.5 | --- |
| 4 | Compressive Strength @28 days in N/mm$^2$ (Min.)<br>a) Test Sample<br>b) Plain Cement mortar cube<br>c) Comparative Strength in percent | <br><br>40.2 Mpa<br>47.6 Mpa<br>84.51% | <br><br>---<br>---<br>Not less than 80% of the strength corresponding to plain cement concrete Mortar cubes | <br><br>---<br>---<br>--- |
| 5 | Particle retained on 45 microns IS Sieve, percent, (Max.) | 17 | 34 | 50 |

**3.2.1 Pulverized Fly Ash**
Pulverized fly ash used is obtained from the source Adani-Dahanu, conforming to IS: 3812:2013 / Reaffirmed (2017). The specific gravity of the fly ash is 2.23. The minimum fineness-specific surface in m2/kg found by the Blaine Air Permeability method is 334. The maximum particle retained on 45 microns IS Sieve is 17 %. Table 5 gives more details about the material.

**3.2.2 Micro Silica**
Micro silica used is from Elcem920D. It confirms the chemical requirements as per IS: 15388 -2013, reaffirmed-2017, Table-1, clause-4.0. The physical properties of PFA confirm ASTM C 1240-15 and IS: 15388:2003 (Table-1, Clause 4.0). The loss of ignition of microsilica is 3.38 % and moisture content is 0.09 %. Tables 6 & 7 give more details about the material.

**Table 6: Laboratory test report on physical properties of micro silica**

| Sr. No. | Test Conducted | Results | Test Method | Requirement/Limit |
|---|---|---|---|---|
| 1 | Specific Gravity(gm/cc) | 2.40 | IS:1727:1967/ RA:2018 | --- |
| 2 | Compressive Strength @7 days in N/mm$^2$ (Min.)<br>Test Sample<br>b) Plain Cement mortar cube<br>c) Accelerated pozzolanic strength activity index with Portland cement at 7 days, percent | <br>30.0 Mpa<br>30.1 Mpa<br>99.7% | ASTM C 1240-15 | ASTM C 1240-15 Accelerated pozzolanic strength activity index with Portland cement at 7 days, min percent of control 105 |
| 3 | Particle retained on 45 microns IS Sieve, percent, (Max.) | 3 | IS:1727:1967/ RA:2018 | IS: 15388:2003 (Table-1, Clause 4.0<br>2) Max. 10% |

**Table 7: Laboratory test report on chemical properties of micro silica**

| Sr. No. | Test | Micro silica Result % | Requirement as per IS:15388: 2013, RA:2017, Table-1, Clause 4.0 |
|---|---|---|---|
| 1 | Silicon Dioxide (as $SiO_2$) | 93.43 | 85.0 % Min. |
| 2 | Loss On Ignition (as LOI) | 3.38 | 4.0 % Min. |

| | | | |
|---|---|---|---|
| 3 | Moisture (as MIV) | 0.09 | 3.0 % Min. |
| 4 | Available Alkali(as $Na_2O$) | 0.38 | 1.5 % Min. |

**3.2.3 Ground Granulated Blast Furnace Slag (GGBS)**

The ground granulated blast furnace slag is confirmed to BS EN 15167-1 (2006). The relative density was given as 2.9 and its chemical composition is given in Table 8. The loss on ignition is 5.46%.

**Table 8: Laboratory test report on chemical properties of GGBS**

| **Sr. No.** | **Test Conducted** | **Requirement as per IS:16714:2018** | **Test Result** |
|---|---|---|---|
| 1 | Fineness $m^2/kg$ (Min.) | 320 (Min.) | 384 |
| 2 | Specific Gravity(gm/cc) | | 2.90 |
| 3 | Residue by weight basis on 45 microns, percent, | | 4.30 |
| 4 | Manganese oxide (MnO)% | 5.50(Max.) | 0.22 |
| 5 | Magnesium oxide (MgO)% | 17.00(Max.) | 7.86 |
| 6 | Sulphide Sulphur (S)% | 2.00(Max.) | 0.54 |
| 7 | Sulphate (as $SO_3$)% | 3.00(Max.) | 0.19 |
| 8 | Insoluble residue, % | 3.00(Max.) | 0.16 |
| 9 | Chloride content, % | 0.10(Max.) | 0.004 |
| 10 | Loss of ignition, % | 3.00(Max.) | 0.28 |
| 11 | Moisture content, % | 1.00(Max.) | 0.022 |
| 12 | Glass content, % | 85 (Max.) | 98.30 |

| **Sr. No.** | **Test Conducted** | **Requirement as per IS:16714:2018** | **Test Result** |
|---|---|---|---|
| Slag Activity Index (SAI) % | | | |
| 1 | 7 days | Not less than 60 % of control OPC 43 Grade cement mortar cube | 69.95 |
| 2 | 28 days | Not less than 75 % of control OPC 43 Grade cement mortar cube | 88.95 |
| Chemical Moduli | | | |
| 4 | $(CaO+MgO+1/3Al_2O_3)$ / $SiO_2 +2/3Al_2O_3$ | 1.00 (Min.) | 1.09 |
| 5 | $(CaO+MgO+Al_2O_3)$ / $SiO_2$ | 1.00 (Min.) | 1.81 |

**3.2.4 Admixture**

The admixture Sika Viscocrete 5210N is used as a superplasticizer for improving fluidity and viscosity. The relative density of the admixture is 1.11 and the pH is 5.96.

Sika Concrete 5210 N is used to help achieve the required fluidity in the mix. It also helps to increase the workability and retention period of the concrete mix.

Three test cubes for each test and each test age are cast as specified in Table 3.11 for the tests mentioned. In this study, there are five different combinations of trials are proposed and five test parameters studied. All the tests were conducted after casting the trails at the age of 28 days and 56 days.

High-strength concrete is that grade of concrete that has a 28-day characteristic compressive strength of 65N/mm$^2$ or above. In the manufacturing of concrete specially selected cementitious materials, admixtures, and superplasticizers are used. Attaining a low water-to-cementitious materials ratio is essential in high-grade concrete. To achieve high strength concrete optimum proportions are selected, considering the cement and other cementitious material properties, aggregate quality, aggregate gradation, paste volume, admixture type, and dosage and mixing [30].

As per IS 10262-2019[30], concrete mix proportioning guidelines suggest the use of a maximum 20 mm size of aggregates for M65 to M80 grade of concrete, and for grades higher than M80, the aggregate size ranging between 10mm to 12.5mm be used.

## IV. Tests performed for assessment of strength and durability

The test methods for the materials used are also mentioned in their material testing reports. The consistency in all mixing procedures and all other things is maintained to get accurate and comparable results in this research project work. Consistent materials, and test methods for all mixes, the same equipment, the same operator, and the same laboratory environment are used. The materials used were stored at room temperature.

### 4.1 Compressive strength

Quality control in concrete manufacturing can be assured by conducting laboratory or in-situ tests on strength and durability. IS:516-1959 (Reaffirmed 2018) [31], explains the methods and procedures for testing the strength of concrete. Material proportioning, weighing, and mixing are done by the IS code procedure. Each batch of concrete is tested for consistency by the method as described in IS: 1999-1959 [32]. A cubical cast iron mould of size 15 x 15 x 15 cm is used for the casting of specimens. A calibrated compression testing machine (CTM) is used for conducting compressive strength test samples. The compressive strength tests conducted in this study are at the age of 7, 28, and 56 days.

### 4.2 Water permeability

The specimen made for the water permeability test complies with BS EN 12390-8-2009 [40, 41]. The specimen dimensions are by IS 1199 (Part 5): 2018, the tolerances are unimportant in this test. The same provisions are made in IS 516 (Part 2/ sec -1):2018 [68]. Water pressure is applied using an arrangement consisting of a water tank connected to an air compressor through the valve, to adjust the pressure. Steps followed in conducting of Water permeability test as per IS 516 (Part 2/ sec-1):2018.

### 4.3 Rapid Chloride Permeability Test (RCPT)

While conducting the experiment it was observed that there is a high rise in temperature in the case of low-grade concrete when the high charge is passed. Thus, poor-quality concrete looks even worse than it would otherwise. According to ASTM C1202 [42], the precision statement states that in the case of a single operator, the coefficient of variation of single test determination was found to be 12.3%. As per AASHTO T259 (ASTM C 1202), a standard test method is followed to conduct an electrical indication of concrete's ability to resist chloride ion penetration (Rapid Chloride Permeability Test). A core of size 100mm diameter and 50mm thick is cut from the concrete block as a test specimen.

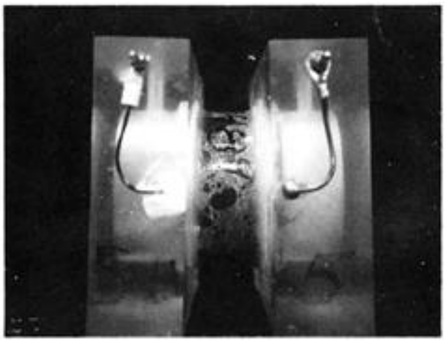

**Fig 1:: Test Apparatus (Specimen ready for test)**

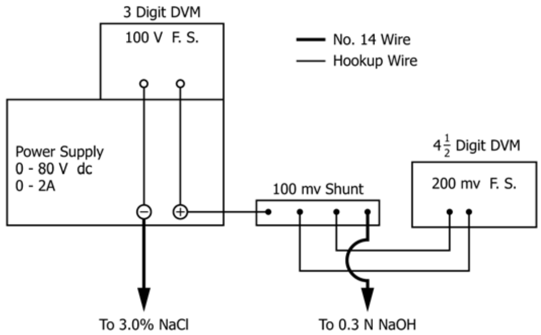


**Fig 2: Electrical block diagram**

The apparatus as shown in Fig. 1 is used to conduct the RCPT test and electrical connections are done as shown in Fig.2. One reservoir is filled with 3.0% NaCl solution and the other one is filled with 0.3 M NaOH solution. A 60 V DC voltage is applied for 6 hours [53]. The total charge passed is determined and used to assess the quality of concrete in terms of chloride ion penetration. ASTM C 1202 TableX1.1 gives a qualitative indication of chloride ion penetrability based on measured values from the tests conducted in the laboratory.

### 4.4 Rapid Chloride Migration Test (RCMT)

The chloride-induced corrosion of reinforcing steel can be assessed by quantifying the chloride transport properties of concrete. There is a need for a reliable prediction model of chloride ingress into concrete exposed to sea water or de-icing salts. There are several short-term and long-term test methods developed by researchers for its prediction. However, looking at time taken and cost of testing; an accelerated test- Rapid Chloride Migration Test (RCMT) is commonly adopted. This test has been adopted as a standard test in Europe. The chloride migration coefficient ($D_{RCM}$) was first time used in the prediction of service life by the European Duracrete project [33].

NT Build 492, Approved 1999-11[34] (Nord Test Method) describes how to perform this Rapid chloride migration test. This test method helps to determine the chloride migration coefficient from a non-steady state migration experiment and it helps to measure the resistance of the material to chloride penetration. However, this migration coefficient cannot be directly compared with chloride diffusion coefficients obtained from other tests.

The specimen used for this test shall be a slice of 100mm diameter and 50mm thickness cut from a cylinder of a minimum length of 100mm. The cylinders and cores should meet the requirements described in NT Build 201[35]. Three specimens shall be tested in each set of tests conducted in the laboratory.

The reagents used in the test include distilled water, $Ca(OH)_2$, NaCl, NaOH, and $AgNo_3$. The test apparatus used in the test includes a water-cooled diamond saw, vacuum container, vacuum pump, migration setup, power supply, ammeter, thermometer, spray bottle, ruler, etc. The specimen is brushed, washed, and wiped off the excess water and then kept in a vacuum container to a pressure range of 10-50 mbar for three hours. The container is filled with saturated $Ca(OH)_2$ solution and then the specimen is immersed in it. The specimen is kept in the solution for 18 +_ 2 hours.
The test procedure includes filling the catholyte reservoir with about 12 liters of 10% NaCl solution. Then the specimen shall be placed on a plastic support in the catholyte reservoir, followed by, the sleeve above the specimen being filled with 300ml anolyte solution (0.3 M NaOH). The anode is immersed in the anolyte solution.

## V. Mechanical Properties of Hardened M70 grade Quaternary Blended Concrete

Compressive strength tests were performed to obtain ultimate load-carrying capacity, ultimate compressive strength, and modulus of elasticity. A total of 75 specimens that include TM1 (control sample), TM2, TM3 TM4, and TM5 are tested during the testing program.
To summarize the results of compressive strength tests, the graphs plotted between the specimen type and 28-day, and 56-day strength are present in Figure 3. The results indicate that there is a significant improvement in the compressive strength of TM2, TM3, TM4, and TM5 as compared to the control specimen.

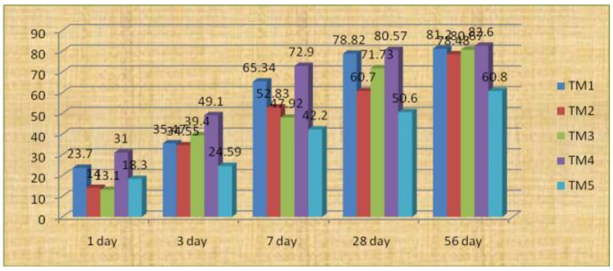


Figure 3: Average compressive strength of test specimens from TM1 to TM5

## VI. Durability Properties of Hardened M70 Grade Quaternary Blended Concrete

### 6.1 Water Permeability

Concrete mixes with varying levels of GGBS replacement (TM2, TM3, TM4, and TM5) exhibited slightly higher water permeability values compared to the control sample (TM1) at both 28 and 56 days. However, TM4, with 25% GGBS replacement, demonstrated superior water permeability performance.TM4's water permeability values complied with the permissible limits specified by IS 516 (Part 2): Sec 1 and BS EN 12390 (Part 8), with an average water penetration depth of 8mm at 28 days and 4mm at 56 days, establishing it as the preferred mix for water permeability.

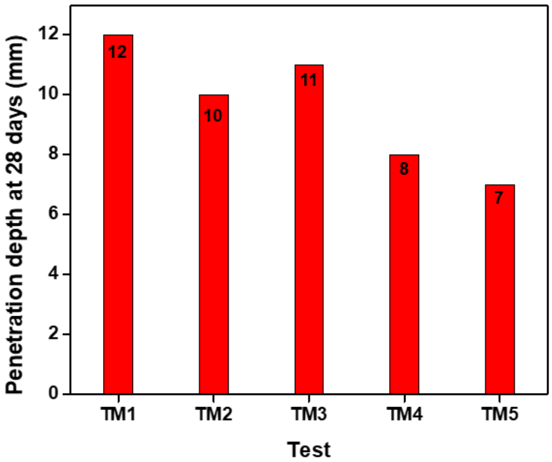


Figure 4: Water Permeability of M70 Grade Concrete

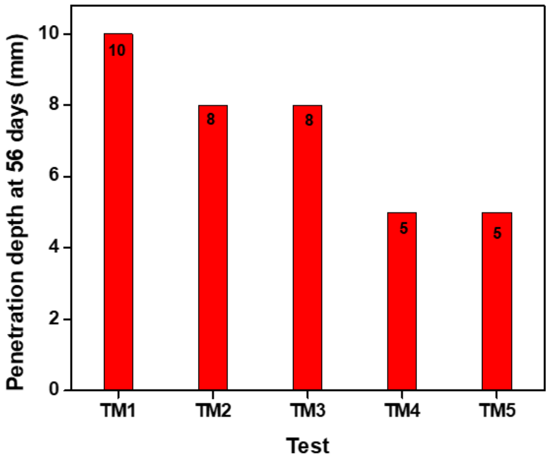


Figure 5: Water Permeability of M70 Grade Concrete

The results indicate that as the proportion of supplementary materials increases in the trial mixes, the water permeability decreases. Trial Mix 4, with the highest percentage of GGBS and a balanced blend of other materials, demonstrated the lowest water permeability among the trial mixes.

### 6.2 Rapid Chloride Penetration

The resistance of cement-based materials to chemical attack is mainly due to the permeability and alkalinity of concrete. To check the penetration of chloride RCPT test was conducted. This test was performed as per the procedure written in ASTM C 1202.

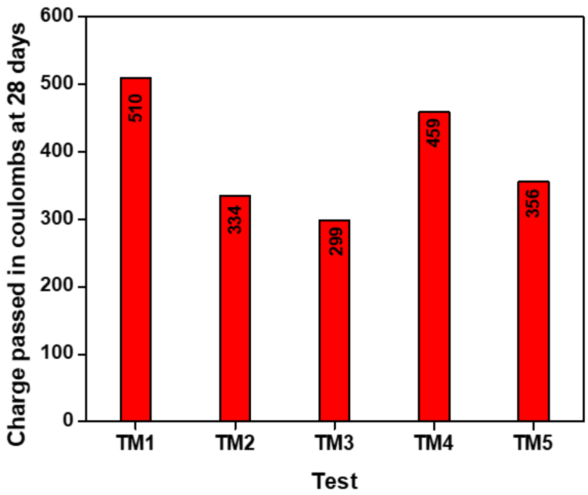


Figure 6: Chloride Penetration at 28 days (RCPT)

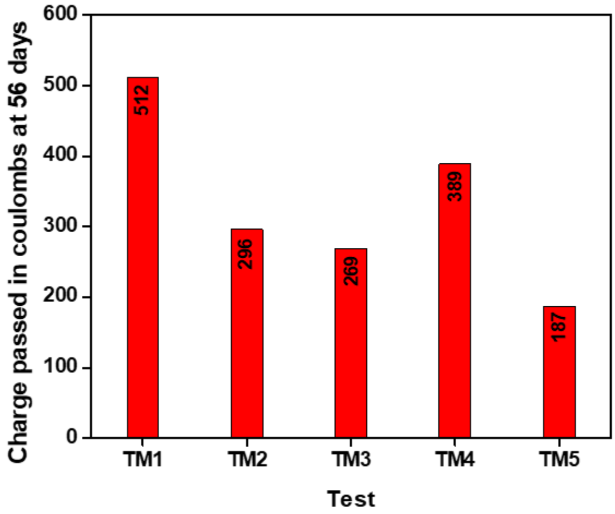


Figure 7: Chloride Penetration at 56 days (RCPT)

The RCPT results indicate that the trial mixes with higher proportions of supplementary materials exhibit improved resistance to chloride ion penetration. Trial Mix 4, with the highest percentage of GGBS, demonstrated the lowest chloride ion penetration among the trial mixes. Comparing the trial mixes with the controlled sample, it is evident that all trial mixes exhibit enhanced resistance to chloride ion penetration. The controlled sample, containing 100% OPC, showed higher chloride ion penetration, emphasizing the positive impact of supplementary materials on improving durability.

The findings suggest that the inclusion of GGBS, Micro Silica, PFA, and Super Plasticizer in varying proportions contributes to the enhanced durability of M70 grade concrete, as evidenced by improved resistance to chloride ion penetration.

**6.3 Rapid Chloride Migration**

The Rapid Chloride Migration Tests were conducted on M70 Grade Concrete. The study aimed to assess the durability of blended M70 grade concrete compared to a controlled sample, using OPC (Ambuja 53 Grade cement), GGBS (JSW certified), Micro Silica, PFA (Adani-Dahanu), and a Super Plasticizer (Sika Viscocrete 5210 N). Five different trial mixes were formulated with varying compositions, and their Rapid Chloride Migration Test results were compared with the controlled sample.

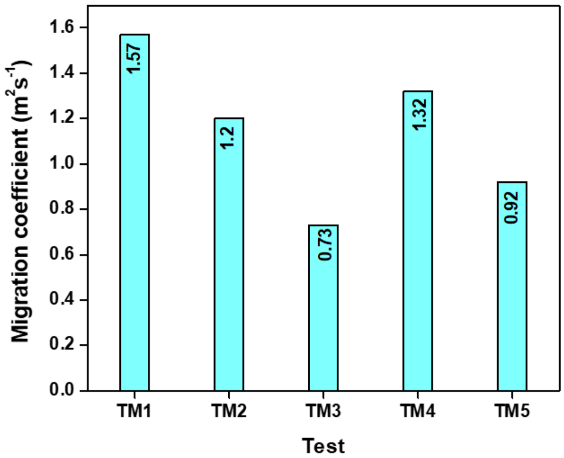


Figure 8: Chloride Migration at 28 days (RCMT)

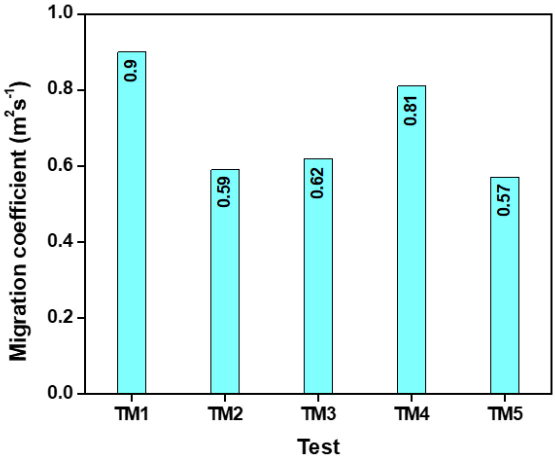


Figure 9: Chloride Migration at 56 days (RCMT)

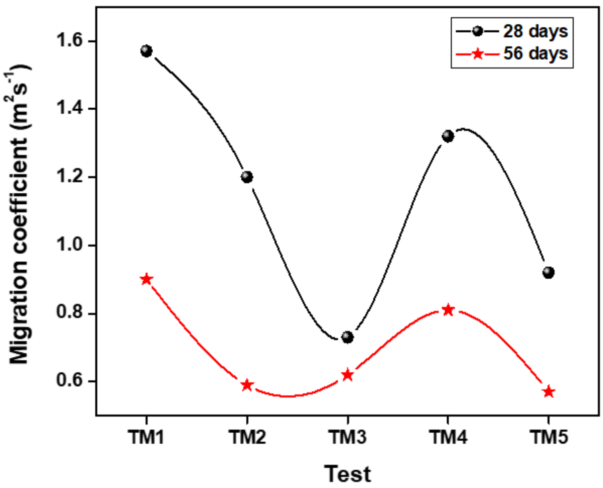


**Fig 10: Comparison of Migration coefficients at 28 days & 56 days**

TM5 recorded the lowest migration coefficient at 56 days, with the least average chloride penetration depth among the tested trials. TM2, TM3, and TM4 are identified as preferred mixes, meeting the standards for migration coefficient values.

**6.4 Electrical resistivity**

This section presents the results and discussions of the thesis, focusing on the subtopic of Electrical Resistivity Tests conducted on M70 Grade Concrete. The study aimed to assess the durability of blended M70 grade concrete compared to a controlled sample, using OPC (Ambuja 53 Grade cement), GGBS (JSW certified), Micro Silica, PFA (Adani-Dahanu), and a Super Plasticizer (Sika Viscocrete 5210 N). Five different trial mixes were formulated with varying compositions, and their Electrical Resistivity Test results were compared with the controlled Sample

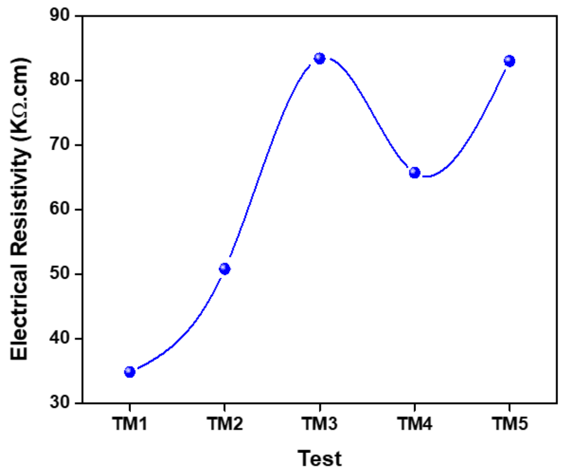


**Fig 11: Electrical Resistivity of Concrete (28 days)**

Two trials demonstrated satisfactory electrical resistivity when utilizing quaternary blended concrete with SCMs for M70 grade concrete.

TM3 and TM5 exhibited the highest electrical resistances among the tested trials, surpassing durability criteria specified by AASHTO TP95 based on the charge passed as per ASTM C1202. However, TM5 was rejected due to its failure to meet strength criteria. These findings underscore the importance of electrical resistivity as a durability indicator in concrete mix design.

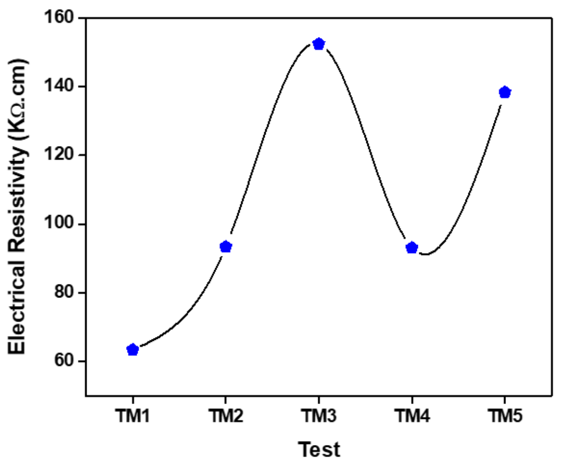


**Fig 12: Electrical Resistivity of Concrete (56 days)**

The findings of this study underscore the technological, financial, and ecological benefits offered by the studied and recommended combinations. However, further advanced research is imperative to develop optimal blending combinations that can effectively replace Ordinary Portland Cement (OPC). Consequently, concretes blended with Supplementary Cementitious Materials (SCMs) emerge as a viable and recommended option for the construction and infrastructure industries, contingent upon specific strength and durability requirements.

These findings not only contribute to the enhancement of concrete performance but also advocate for sustainable practices in the construction sector, aligning with contemporary environmental concerns and industry demands.

The results indicate that trial mixes with higher proportions of supplementary materials exhibited increased electrical resistivity. Trial Mix 4, with the highest percentage of GGBS, demonstrated the highest electrical resistivity among the trial mixes.

## VI. Conclusion

The incorporation of Supplementary Cementitious Materials (SCMs) in concrete has shown significant improvements in strength, durability, and microstructure compared to conventional concrete. Laboratory reports indicate that SCM-based concrete exhibits enhanced strength, durability, and improved microstructure. Quaternary blended concrete mixes (TM2, TM3, TM4, & TM5) demonstrated the potential for achieving higher long-term compressive strengths compared to the control mix (TM1). Specifically, TM4 emerged as the preferred mix with notable strengths at 28 and 56 days, surpassing the control mix. The synergistic effect between Pulverized Fly Ash (PFA), Ground Granulated Blast Furnace Slag (GGBS), and Micro silica led to enhanced performance, offering economic and environmental advantages by reducing Ordinary Portland Cement (OPC) content.

Water permeability tests revealed that concrete mixes with GGBS replacement exhibited slightly higher water permeability values, with TM4 showing superior performance. Rapid Chloride Penetration Test (RCPT) results indicated low chloride ion penetrability values for all samples, meeting standards for concrete production. Rapid Chloride Migration Test (RCMT) results confirmed the benefits of incorporating SCMs, with all quaternary blended mixes meeting permissible limits. Electrical resistivity tests highlighted the importance of this property as a durability indicator, with TM3 and TM5 exhibiting high electrical resistances.

In conclusion, the study emphasizes the technological, financial, and ecological benefits of using SCMs in concrete mixes. Further research is needed to optimize blending combinations to effectively replace Ordinary Portland Cement (OPC). The findings support the use of SCMs as a sustainable and recommended option in the construction industry, aligning with environmental concerns and industry demands for enhanced concrete performance.

**Conflict of interest**

The authors declare that we have no conflict of interest directly or indirectly by any financial or personal means for the submitted manuscript work.

**Acknowledgment:**
No funds have been received for this research work.

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