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Reviving Time-Degraded Cement: Sustainable Performance and Structural Resilience of Concrete with Hybrid Admixtures

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Abstract: Long storage of cement under humid or improperly controlled conditions may lead to pre-hydration, particle agglomeration, and loss of reactivity, which lead to material wastage and economic loss. This study explores the possibility of using time degraded cement in M25 grade concrete with the addition of Glass powder, Ground Granulated Blast Furnace Slag (GGBS), Silica fume and Chemical admixtures. Four mixtures were created: a fresh PPC control mixture and three mixtures with varying amounts of time degraded cement and supplementary cementitious materials. Workability was determined by slump-cone test and compressive strength was determined at 7, 14 and 28 days. Selected mixtures were also tested by Ultrasonic Pulse Velocity and carbonation-depth tests. The slump values measured were between 70 and 93 mm, which is satisfactory but not the desired workability. The 28-day values for the control mixture, glass-powder mixture and GGBS-based mixture were 29.20, 30.50 and 30.60 MPa, respectively. The mixture with GGBS and silica fume had 24.90 MPa. Hence, the maximum strength was achieved using 10% time degraded cement and GGBS. The results show the potential of recovering partially degraded cement with the hybrid binder systems, with the need for replicate testing and long-term durability testing prior to structural application.

Keywords: Time-degraded cement; GGBS; glass powder; compressive strength; sustainable concrete.

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I. INTRODUCTION

Cement is the principal binding material in concrete, and its performance depends on its hydration and microstructural development. The hydration of cement involves complex reactions that progressively form the cementitious matrix responsible for strength development and other properties of concrete [7], [12]. When cement is exposed to moisture during prolonged or improper storage, partial hydration and agglomeration of cement particles may occur, which can adversely affect its subsequent performance [6], [7]. Consequently, time-degraded or expired cement may have reduced reactivity and may not perform in the same manner as fresh cement. The disposal of such material can also contribute to material wastage and increase the demand for fresh cement.

The reuse of time-degraded cement could provide a potential sustainability benefit if its remaining cementitious activity can be supplemented with suitable supplementary cementitious materials (SCMs). GGBS has been widely investigated as a cement replacement material and has demonstrated beneficial effects on the strength efficiency and performance of concrete [4]. Silica fume, because of its very fine particle size and high reactivity, can contribute to the refinement of the cementitious matrix and improvement of concrete properties [5], [13]. Finely ground waste glass can also act as a pozzolanic material because of its reactive silica content, providing an opportunity for the value-added utilisation of waste glass in concrete [9], [10]. The use of glass powder as a cement replacement has also been investigated under field conditions, demonstrating its potential for incorporation into concrete mixtures [2].

The previous studies have specifically examined the use of expired or hardened cement and their effect on bond, microstructure and properties related to durability under appropriate conditions and reported improvement in these properties [6]. Further, research on GGBS and other SCMs has shown that the performance of these materials can be variable with replacement level, mixture composition and curing conditions [4, 5]. The combination of time-degraded cement, GGBS, silica fume, glass powder and chemical admixtures needs to be investigated as it may have an impact on workability, strength development and properties related to durability [4, 5, 6, 13]. Hence, the performance of such a hybrid binder system must be determined experimentally and not based on the individual performance of its constituents. Hence, the present study aims to explore the possibility of using time degraded Portland Pozzolana Cement (PPC) in M25 grade concrete with various hybrid binder systems. A fresh-PPC control mixture and three modified mixtures were

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tested for workability, compressive strength at 7, 14 and 28 days, Ultrasonic Pulse Velocity (UPV) and carbonation depth. The design of concrete mixture proportions was done as per IS 10262:2019 [17] and the testing procedures used were in accordance with the relevant Indian Standards for concrete strength [19], UPV [28] and carbonation depth [22]. The purpose of this study is to investigate whether the time-degraded cement can be used as a component of the binder in the concrete and still have an acceptable performance, with less waste of materials by using more resource-efficient construction methods.

II. METHODOLOGY

The experimental programme was designed to examine the possibility of using time degraded cement in M25 grade concrete without affecting the basic mechanical and quality properties. The study used a combination of conventional concrete ingredients and industrial by-products and chemical admixtures to develop a hybrid binder system. The entire investigation was conducted by material characterization, mix preparation, fresh-concrete testing, specimen curing, hardened-concrete testing, and comparison of data.

Initially, fresh PPC and time-degraded PPC were collected and analyzed. The storage period, the condition of the packaging, exposure of moisture, visible lumps, colour, texture, fineness, specific gravity and setting characteristics of the cement were noted. This initial evaluation was significant as the moisture exposure to cement during extended or improper storage may affect reactivity [7, 12]. The condition of the time-degraded cement was compared to that of fresh PPC, which was gently sieved before use to remove large hardened particles. Physical properties of the cement were tested and compared with the relevant requirements and test methods for hydraulic cement [30].

The supplementary cementitious materials were then characterized. Specific gravity, fineness, particle size characteristics, moisture condition and general physical appearance of the GGBS, glass powder and silica fume were determined. The use and characterization of GGBS and silica fume was taken into consideration based on the relevant material specifications [23] and [24]. Clean waste glass was washed, dried, crushed, ground and sieved to the required fineness to prepare glass powder. Previous studies [2], [9] and [10] have reported the use of finely ground glass as a supplementary cementitious material. The fine and coarse aggregates were also subjected to grading, specific gravity, water absorption, moisture content, bulk density and other physical properties tests as per the relevant aggregate specifications and test procedures [25] and [26]. The mixing and curing of the concrete were done with clean water and the required chemical admixtures were measured based on the designed binder mass and required dosage [13].

Four concrete mixes were made with the M25 mix. The fresh-PPC control mixture was sample A. The time degraded cement and supplementary cementitious materials were in different proportions in the samples B, C and D. Sample B was made with the addition of glass powder and a latex admixture, Sample C was made with the addition of GGBS and silica fume and TEA, and Sample D was made with the addition of GGBS and a PCE-based admixture. The proportions of the mixtures were based on the total binder content, the amount of aggregates, the target workability, the exposure condition and the water to binder ratio. The mix proportions for the concrete were designed based on IS 10262:2019 [17]. The water to binder ratio was determined for all of the cementitious materials, including fresh cement, time degraded cement, GGBS, silica fume and glass powder.

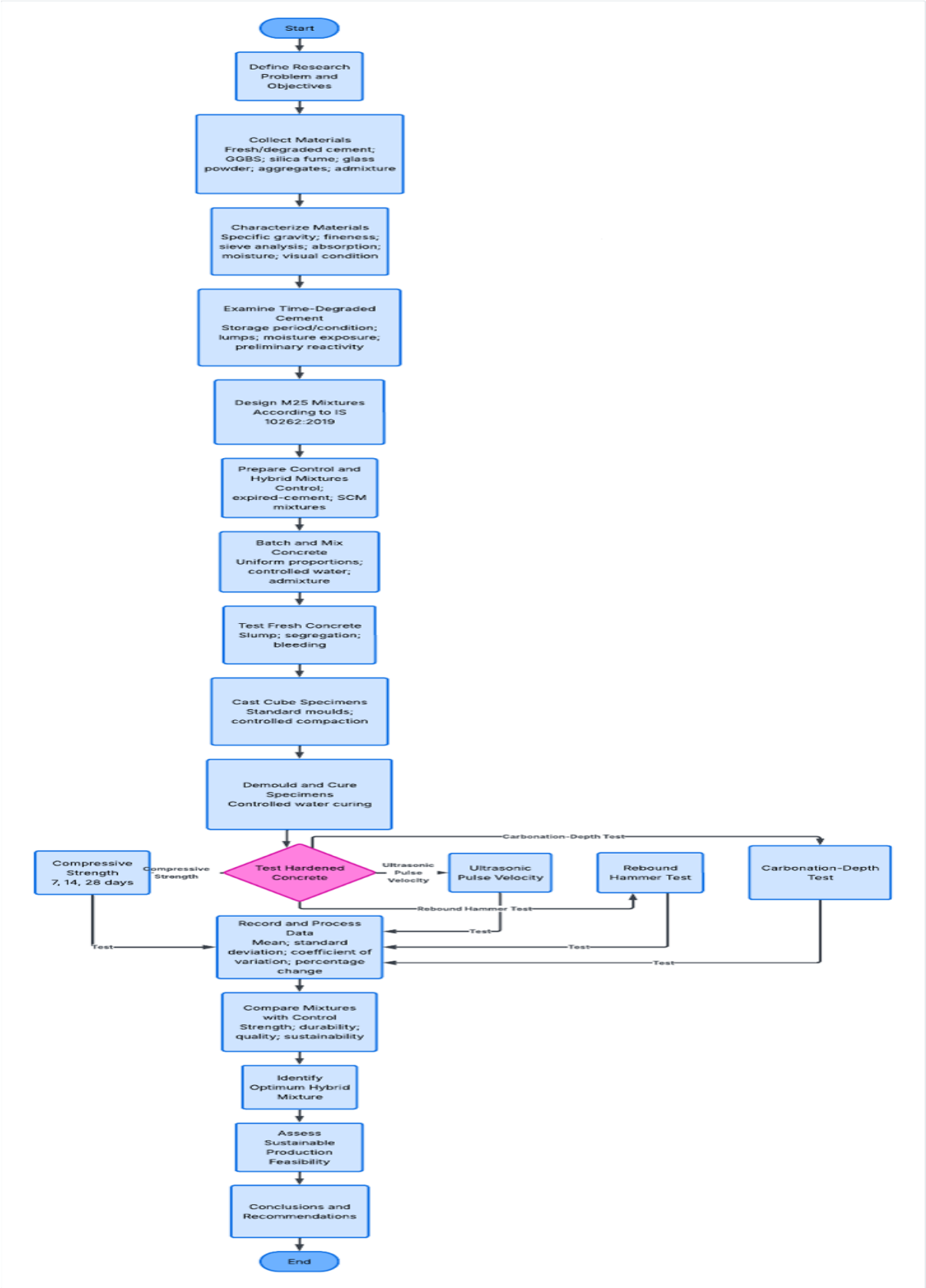
The workability of each fresh mixture was measured using the slump-cone test in accordance with the relevant provisions for determination of slump [21]. The slump values measured were compared with the target slump and observations were made on the cohesion, segregation, bleeding and ease of placement. Concrete cubes of 150 mm and mortar cubes of 70 mm were then cast. The specimens were compacted in the same manner and were left undisturbed until demoulding. They were then removed from the mould and cured in clean water until the required testing ages. The procedures for preparation and testing of hardened concrete were adhered to as per the relevant Indian Standards [19].

Compressive strength was determined at 7, 14 and 28 days as per IS 516 (Part 1/Sec 1):2021 [19]. The results were used to assess strength development and compared to the control. Selected concrete samples were also tested for an indirect indication of internal continuity and uniformity by Ultrasonic Pulse Velocity (UPV) testing, as per the relevant testing procedure [28]. The adopted procedure of the indicator based method was used to conduct carbonation-depth testing at the selected age as per IS 516 (Part 5/Sec 3):2021 [22]. The exposure condition, curing history, test age, indicator concentration and measurement locations were documented.

Lastly, the results were compared based on workability, compressive strength, UPV, carbonation depth, strength development and percentage change with the control mixture. Where actual replicate results were available, mean values, standard deviations and coefficients of variation were considered. The following flow chart shows the entire sequence

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of experiments from collection of materials to final interpretation and identification of the selected mixture based on the experimental performance measured.



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III. LITERATURE REVIEW

The ageing of cement, the use of supplementary cementitious materials, waste-glass utilization and utilization of deteriorated cement have been studied by several researchers. The following studies are particularly relevant to the current research.

3.1 Neville: Properties of Concrete

Neville explained the significance of cement storage, hydration, mix proportioning and concrete durability [8]. During storage, moisture can cause changes in the cement that can affect its performance, such as hydration and particle agglomeration. This paper gives general technical background information on the assessment of time degraded cement prior to use in concrete [8].

3.2 Taylor: Cement Chemistry

The chemical reactions involved in the hydration of cement and the formation of hardened cement paste were explained by Taylor [7]. The discussion of the hydration products and the cement chemistry provides some explanation of how changes prior to mixing can affect the behaviour of the cement particles. The concept is significant in the present study because the time degraded cement may consist of partially hydrated particles which may contribute differently to the strength development than fresh cement [7], [12].

3.3 Mehta and Monteiro: Concrete Microstructure, Properties, and Materials

Mehta and Monteiro pointed out the correlation between the mechanical and durability properties of concrete and its microstructure [3]. Their work describes the role of water and supplementary cementitious materials in the formation of the cementitious microstructure. Reactive supplementary materials may help to refine and modify the cement paste and interfacial transition zone [3]. This gives theoretical support to investigate the combinations of time degraded cement with GGBS, silica fume and glass powder.

3.4 Shayan and Xu: Glass Powder in Concrete

Shayan and Xu studied the use of finely ground waste glass as pozzolanic material in concrete [9]. Their work showed that the fine ground waste glass could react pozzolanic and was useful to the performance of concrete. Factors like particle size, replacement level and curing condition affect the performance of glass powder [2, 9]. The results of this work are used to validate the use of glass powder in Sample B, which was mixed with time-degraded PPC.

3.5 Ganesh Babu and Sree Rama Kumar: Efficiency of GGBS

Ganesh Babu and Sree Rama Kumar studied the cementitious performance of GGBS in various replacement percentages [4]. They found that the strength contribution of GGBS is related to replacement percentage, water-to-cementitious-material ratio and curing age [4]. This is significant for Samples C and D where GGBS was incorporated into the hybrid binder system.

3.6 Sabir, Wild, and Bai: Pozzolanic Materials

Sabir, Wild and Bai reviewed the use of metakaolin and calcined clays as pozzolanic material and discussed the behaviour of highly reactive supplementary cementitious material [5]. Their work is background to the understanding of the role of finely divided reactive materials in cementitious systems. It has also been studied when used with other supplementary cementitious materials to enhance the durability and chloride resistance of concrete [16]. These properties are applicable to Sample C, which had GGBS and silica fume.

3.7 Chofore: Expired Cement Blended with GGBS

The bond, microstructure and durability-related performance of hardened cement produced using GGBS were studied by Chofore et al. [6]. This research is directly applicable to the present study as it involved the reuse of deteriorated cement instead of its immediate disposal. The results show that the use of expired cement in combination with GGBS can affect bond, microstructure and durability properties [6]. This serves as a basis for further research on hybrid binder systems with time-degraded cement.

3.8 Supporting Research on Hydration and Durability

Scrivener, Juilland, and Monteiro reviewed advances in understanding cement hydration and highlighted the importance of hydration mechanisms, reaction kinetics, and the formation of hydration products [12]. Their work is useful for interpreting differences between fresh PPC and time-degraded PPC.

Research on carbonation has also examined the relationship between carbonation and concrete durability. Liu, Sun, and Qu reviewed the coupled effects of stress and carbonation on concrete durability and highlighted the influence of concrete characteristics and environmental conditions on carbonation behaviour [14]. In the present study, these

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considerations are relevant when interpreting carbonation-depth measurements, including the zero-carbonation-depth observation recorded for Sample B at 28 days.
The use of chemical admixtures also requires attention to dosage and compatibility. ACI Committee 212 describes the use of chemical admixtures for modifying properties such as workability, setting, water demand, strength development, and durability of concrete [13]. This is relevant to the use of latex-based admixture, TEA, and PCE-based admixture in Samples B, C, and D.

3.9 Research Gap

The reviewed literature shows that cement hydration and changes in cement particles can influence subsequent cementitious performance [7], [8], [12], while GGBS, silica fume, and glass powder have been investigated as supplementary materials for improving or modifying concrete performance [4], [5], [9], [10], [16]. Previous research has also demonstrated the potential for combining expired cement with GGBS [6].
The literature surveyed in this study, however, does not give much information on the use of time degraded PPC, GGBS, silica fume, glass powder and chemical admixtures in M25 grade concrete. The interrelationship of these materials in terms of workability, strength development, UPV and carbonation behaviour is thus in need of further experimentation. The present study fills this gap by comparing a fresh-PPC control mixture with three modified mixtures, where the cement is time degraded and the binder system is a hybrid of PPC and different admixtures. The workability, compressive strength at 7, 14 and 28 days, UPV and carbonation depth of the mixtures are assessed. The study also investigates the reusability of the time degraded cement as a binder component for achieving the desired performance of M25 grade concrete.

3.10 Research Objectives

The objectives were formulated to be measurable through the experimental programme:

- To characterize the physical condition and reactivity-related properties of the time-degraded PPC used in the concrete mixtures [7], [8], [12].
- To investigate the effect of replacing a controlled proportion of fresh PPC with time-degraded PPC on the workability and compressive strength of M25-grade concrete at 7, 14, and 28 days [17], [19].
- To evaluate the influence of glass powder, GGBS, and silica fume on the strength development of concrete containing time-degraded cement [4], [5], [9], [10].
- To compare the performance of the hybrid mixtures with the fresh-PPC control using slump, compressive strength, UPV, and carbonation-depth results [19], [21], [22], [28].
- To identify the mixture showing the most favourable measured performance based on workability, compressive strength, UPV response, and carbonation behaviour.
- To examine the relationship between compressive strength and UPV results for the developed concrete mixtures [19], [28].
- To assess the practical and sustainability potential of reusing time-degraded cement together with industrial by-products while maintaining acceptable M25-grade concrete performance [4], [9], [10].

IV. MATERIALS USED

4. MATERIALS USED

The experimental programme was conducted with conventional concrete materials and time-degraded cement, industrial by-products and chemical admixtures. The materials were chosen for their particular application: to investigate if the performance of the stored cement could be enhanced by a well-designed hybrid binder system [4], [6], [9], [10].

4.1. Fresh Cement

Fresh PPC was used as the main binder in the control mixture. It was used as the reference performance to which all mixtures made of time-degraded cement were compared. Type, grade, manufacturer, manufacturing date, and storage condition of the cement were identified. Prior to use, its specific gravity, fineness, consistency, setting time and soundness were measured following the appropriate cement test procedures [30, 31].

4.2. Time-Degraded Cement

The time-degraded PPC was obtained by extended storage under the conditions of the selected site or laboratory. It was noted how long it was stored, its packaging condition, moisture exposure, colour, texture and presence of visible lumps. The material was gently sieved to remove large hardened particles and subjected to specific gravity, fineness, moisture content and preliminary strength contribution tests. The reactivity of the particles and the mechanisms of their hydration are closely correlated with the hydration and development of cementitious products [7, 12]. Hence, cement which has been exposed to moisture for a long period of time may have changes in physical condition and performance. The cement

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used was only a controlled partial replacement and the use of the time-degraded cement in the concrete mixtures was not based solely on the storage age, but on the laboratory observations [6]–[8].

4.3. Ground Granulated Blast Furnace Slag

The supplementary cementitious material used was GGBS. It is a finely ground industrial by-product with latent hydraulic properties and has been extensively studied as a partial replacement for cement in concrete [4, 23]. GGBS can also undergo cementitious reactions in the alkaline environment of the cement paste and generate further hydration products that can affect the strength and pore structure at later ages [4], [12]. Specific gravity, fineness, moisture content, bulk density, particle size distribution and chemical composition of the GGBS were tested. It was also considered to be conforming to IS 16714:2018 [23].

4.4. Silica Fume

The addition of silica fume was due to its very fine particles and high pozzolanic reactivity. Silica fume may react with the calcium hydroxide produced during cement hydration and help to produce more cementitious products [5]. It can also change the micro-structure and decrease the pore connectivity of cement-based materials due to its very fine particles [5, 16]. Since silica fume has a high surface area, the addition of silica fume can affect the water requirement and workability of concrete [5]. It was therefore kept in dry conditions, measured carefully and spread out gently when mixing. The material was assessed based on the requirements of IS 15388:2003 [24].

4.5. Glass Powder

Clean waste glass was converted to glass powder. The glass was washed, dried, crushed, finely ground and sieved to get the desired particle size. The finely ground waste glass is found to contain reactive amorphous silica and has been studied as pozzolanic material in concrete [2, 9, 10]. The glass powder was used to derive two benefits: firstly to add a reactive mineral material to the binder, and secondly to offer a pathway for the use of waste glass in concrete [9, 10]. The particle size, specific gravity, colour, grinding method, moisture content and replacement percentage were noted as these parameters can affect its performance as a supplementary cementitious material [2, 9]. The suitability of waste glass for use in concrete was also assessed for the potential of alkali–silica reaction (ASR) [9] and [10].

4.6. Fine Aggregate

The fine aggregate used was manufactured sand. It filled the voids between the coarse-aggregate particles and helped to impart workability, grading, density and stability to the fresh and hardened concrete. The properties of fine aggregate were tested according to the IS 383:2016 [25]. The manufactured sand was tested for sieve grading, fineness modulus, specific gravity, water absorption, moisture content, bulk density, and deleterious materials (silt or others) in accordance with the aggregate-testing procedures [25] and [26]. The properties of the aggregate were taken into consideration in the mix proportioning to achieve the desired performance of the concrete.

4.7. Coarse Aggregate

Coarse aggregate 20 mm MNS was crushed to create the load bearing skeleton of the concrete. The aggregate particles were clean, hard and contained little dust and other impurities. Coarse aggregate has been selected based on IS 383:2016 [25]. The specific gravity, water absorption, grading, aggregate crushing value, impact value, abrasion value, flakiness index and elongation index of the coarse aggregate were determined using the appropriate aggregate specifications and test procedures [25] and [26]. The internal voids were minimised and the concrete mix was packed by maintaining proper grading.

4.8. Water

Mixing and curing were done with clean water. The water was kept free from oil, acids, organic matter, excessive salts and other substances that might impair the cementitious reaction or performance of the concrete. The same water source was used in the entire experimental programme. The amount of water used for each mixture was accurately determined and adjustments were made for moisture and absorption condition of the aggregates as needed. The water content was taken as a part of mix-proportioning process as per IS 10262:2019 [17].

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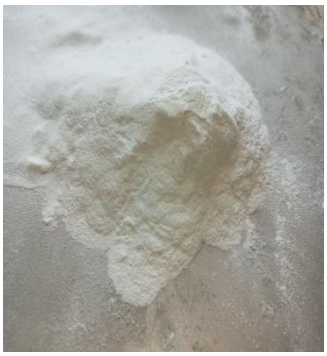
			
FRESH CEMENT	TIME DEGRADED CEMENT	GGBS	SILICA FUME
			
GLASS POWDER	FINE AGGREGATE	COARSE AGGREGATE	WATER

FIG. 4.1 MATERIALS USED

4.9. Chemical admixtures

Chemical admixtures were used to improve the workability and dispersion of the hybrid binder systems [13]. Latex, triethanolamine (TEA), and polycarboxylate ether (PCE)-based admixtures were used in different mixtures. The incorporation of GGBS, silica fume, and glass powder can influence the water demand and workability of concrete [4],[5],[9]. The admixtures were therefore added at controlled dosages based on the binder mass and manufacturer's recommendations [13]. Their type, density, viscosity, solids content, pH, dosage, and compatibility with the cementitious materials were recorded. Proper dosage and compatibility are important when chemical admixtures are used in cement-based mixtures [13]. The admixtures were used as performance-enhancing materials and were not considered as replacements for cement [13].

		
LATEX	TEA	PCE

Fig. 4.2 CHEMICAL ADMIXTURES

4.10. Cube moulds and curing facilities

Standard cube moulds were used for preparing the concrete and mortar specimens in accordance with the relevant concrete-testing procedures [19]. The moulds were cleaned and lightly coated before casting to facilitate proper

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demoulding. Concrete was placed and compacted using the same procedure for all mixtures to ensure uniform specimen quality [19]. After casting, the specimens were kept undisturbed until demoulding and were subsequently cured in clean water. The mould dimensions, compaction method, demoulding time, curing conditions, and curing duration were kept consistent for all mixtures [19]. All specimens were tested at the specified ages to enable a reliable comparison of strength and other measured properties [19], [28].



CUBE MOULDS



CUBE CURING

FIG.4.3 CUBE MOULDS & CUBE CURING

TABLE I: SIEVE ANALYSIS OF FINE AGGEREGATE

Mass of sample taken = 1000 g

S. No.	IS sieve designation	Mass retained (g)	Percentage retained (%)	Cumulative percentage retained (%)	Percentage passing (%)
1	4.75 mm	1	0.1	0.1	99.9
2	2.36 mm	24	2.4	2.5	97.5
3	1.18 mm	423	42.3	44.8	55.2
4	600 µm	216	21.6	66.4	33.6
5	300 µm	187	18.7	85.1	14.9
6	150 µm	105	10.5	95.6	4.4
7	Pan	43	4.3	99.9	0.1
8	**Total**	**999**	**99.9**	—	—

Calculation of fineness modulus
The cumulative percentages retained on the standard sieves, excluding the pan, are:

$$0.1 + 2.5 + 44.8 + 66.4 + 85.1 + 95.6 = 294.5$$

Therefore,

$$\text{Fineness Modulus} = \frac{294.5}{100} = 2.945$$

$$\boxed{\text{Fineness Modulus of Fine Aggregate} \approx 2.95}$$

The fine aggregate obtained a fineness modulus of approximately **2.95**, indicating a medium-to-coarse grading. The material contains a considerable proportion of particles retained on the 1.18 mm and 600 µm sieves, while the quantity

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of material passing the 150 µm sieve is relatively small. This grading can provide satisfactory particle packing and may help control the paste and water demand of the concrete mixture.

TABLE II: PHYSICAL PROPERTIES OF CONCRETE MATERIALS

Material	Specific gravity	Water absorption (%)	Fineness (m^2/kg)	Initial setting time (min)	Final setting time (min)
Fresh cement (PPC)	3.02	—	322	36	595
Time-degraded cement (PPC)	2.86	—	308	57	710
Glass powder	2.51	—	375	—	—
GGBS	2.87	—	405	—	—
Silica fume	2.63	—	14,800	—	—
Fine aggregate (M-sand)	2.76	3.2	—	—	—
Coarse aggregate	2.78	0.40	—	—	—

The fresh PPC had a specific gravity of 3.02 and a fineness of 322 m^2/kg, initial setting time of 36 minutes and final setting time of 595 minutes. The time degraded cement had a slightly lower specific gravity and fineness, along with extended setting times. This change might be linked to moisture exposure, partial pre-hydration and agglomeration during storage.

Silica fume was the finest of the supplementary materials followed by GGBS and glass powder. Silica fume, which is very fine, can also enhance particle packing and pore refinement, but can also increase water requirement and decrease workability. The specific gravities of M-sand and coarse aggregate were 2.76 and 2.78 respectively and their water absorption was relatively low.

V. CONCRETE MIX DESIGN

5.1 Design Basis

The concrete mixtures were designed for M25 grade using PPC as the primary cement. The mix-design procedure was based on IS 10262:2019, while the durability requirements were considered with reference to IS 456:2000. The maximum nominal size of coarse aggregate was 20 mm, and crushed aggregate was used.

TABLE III DESIGN PARAMATERS

Design parameter	Adopted value
Concrete grade	M25
Type of primary cement	PPC
Maximum nominal size of aggregate	20 mm
Type of coarse aggregate	Crushed
Exposure condition	Moderate

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Design parameter	Adopted value
Minimum cementitious-material content	300 kg/m³
Maximum cementitious-material content	450 kg/m³
Adopted standard deviation	4 MPa
Target slump	100 mm
Target mean strength	31.6 MPa

5.2 Target Mean Strength
The target mean strength was calculated using:

$$f_t = f_{ck} + 1.65s$$

where:
- f_t= target mean compressive strength,
- f_{ck}= characteristic compressive strength,
- s= standard deviation.

For M25 concrete:

$$f_t = 25 + 1.65(4)$$

$$f_t = 31.6 \text{ MPa}$$

Thus, the calculated target mean strength was:

$$\boxed{31.6 \text{ MPa}}$$

This value is a **mix-design target** and should not be reported as an experimental compressive-strength result. The highest measured 28-day concrete-cube strength in the present dataset was 30.60 MPa for Sample D.

5.3 Mix Groups
Four mixtures were prepared:
- **Sample A:** Control concrete containing only fresh PPC as the binder.
- **Sample B:** Concrete containing 10% time-degraded PPC and 10% glass powder.
- **Sample C:** Concrete containing 5% time-degraded PPC, 17% GGBS, and 8% silica fume.
- **Sample D:** Concrete containing 10% time-degraded PPC and 10% GGBS.

Cement was not found to be expired in sample A. It was therefore not considered as a time-degraded-cement mixture, but rather as a control mixture. This distinction is important because the performance of Samples B–D was compared to the fresh-PPC reference.

5.4 Water-to-Binder Ratios and Chemical Admixtures
The water to binder ratio was determined by the total mass of cementitious materials, not just the mass of fresh PPC. This method is more suitable where GGBS, silica fume, glass powder and time-degraded cement are used as the binder components.

$$w/b = \frac{\text{mass of mixing water}}{\text{total mass of cementitious materials}}$$

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TABLE IV ADOPTED WATER-TO-BINDERRATIOS AND CHEMICAL ADMIXTURES

Sample	Water-to-binder ratio	Chemical admixture	Nominal dosage
S-A	0.48	None	—
S-B	0.43	Latex-based admixture	0.40% of binder
S-C	0.42	TEA	0.02% of binder
S-D	0.39	PCE-based admixture	0.30% of binder

The chemical admixtures were added to enhance the dispersion and workability, especially in the fine glass powder, GGBS and silica fume mixes. The chemical composition of the latex, TEA and PCE products needs to be reported from the technical data sheets provided by the manufacturer.

The estimated quantities for 1 m³ of concrete are shown in Table 5.5.
The quantities below are estimated quantities for 1m³ of concrete and are based on the mix-design data provided. They should be checked by the absolute-volume method, moisture corrections in aggregates and trial-batch results prior to submission.

TABLE V ESTIMATED QUANTITIES FOR 1M³ OF CONCRETE

Material	S-A (kg/m³)	S-B (kg/m³)	S-C (kg/m³)	S-D (kg/m³)
Fresh PPC	409.5	369.8	302.0	339.6
Time-degraded PPC	—	46.2	21.6	42.4
Glass powder	—	41.0	—	—
GGBS	—	—	73.4	42.5
Silica fume	—	—	34.5	—
Total binder	**409.5**	**457.0**	**431.5**	**424.5**
Fine aggregate	668.2	651.0	689.5	832.6
Coarse aggregate	1125.8	1152.4	1202.8	1149.7
Water	196.6	199.1	193.3	148.9
Chemical admixture	—	1.83	0.09	1.27
Approximate calculated w/b	0.48	0.44	0.45	0.35

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5.6 Material Identification for the Mixes

TABLE VI BINDER COMPOSISTION OF THE FOUR MIXTURES

Binder component	S-A (%)	S-B (%)	S-C (%)	S-D (%)
Fresh PPC	100	80	70	80
Time-degraded PPC	—	10	5	10
Glass powder	—	10	—	—
GGBS	—	—	17	10
Silica fume	—	—	8	—
Total binder system	**100**	**100**	**100**	**100**

The table shows the intended binder proportions. However, because the proportions are based on the total binder system, the mass of each component should be reported in the final paper as well.

5.7 Final Mix Ratios

The approximate aggregate-to-binder ratios are shown below. These are mass ratios and should be interpreted together with Table VII.

TABLE VII FINAL APPROXIMATE MIX RATIOS

Sample	Binder	Fine aggregate	Coarse aggregate	Approximate ratio	Description
S-A	1.00	1.63	2.75	1: 1.63: 2.75	Fresh-PPC control
S-B	1.00	1.43	2.52	1: 1.43: 2.52	Time-degraded PPC–glass-powder system
S-C	1.00	1.60	2.79	1: 1.60: 2.79	Time-degraded PPC–GGBS–silica-fume system
S-D	1.00	1.96	2.71	1: 1.96: 2.71	Time-degraded PPC–GGBS system

This table gives the ratios on a mass basis of the total binder. It is better than only dividing aggregate quantities by the mass of fresh cement as the mineral additions and time degraded cement also contribute to the binder system.

5.8 Mix-by-Mix Description

Sample B: Fresh-PPC + 100 ppm phosphorus

Sample A consisted of fresh PPC, fine aggregate, coarse aggregate and water. No cement, mineral admixture, or chemical admixture was used that was time degraded. The aim of Sample A was to serve as a reference sample for the effect of expired cement and hybrid admixtures.

Sample B: Time degraded PPC and glass powder.

Sample B was composed of 10% time degraded PPC, 10% glass powder and the remaining 80% was fresh PPC. The admixture used was latex based at 0.40% of the binder. The glass powder was added to aid in fine particle packing and to impart possible pozzolanic activity, and the latex admixture was added to enhance workability and cohesion.

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Sample C: Time-degraded PPC, GGBS and silica fume.
The proportions of time-degraded PPC, GGBS and silica fume in sample C were 5%, 17% and 8% respectively. TEA was used at 0.02% of binder. This mixture was formulated to incorporate the latent hydraulic properties of GGBS and the pore refining properties of silica fume. Both materials are fine and reactive, so their impact on water demand and early age strength was verified through experimentation.

Sample C: The PPC and GGBS mix is time degraded.
Sample D consisted of 10% time-degraded PPC, 10% GGBS and PCE 0.30% of binder. The lower water/binder ratio was designed to enhance matrix compaction and strength. The measured data showed that Sample D was the best performing mixture in terms of 28-day concrete-cube strength, but it did not achieve the calculated 28-day concrete-cube strength target of 31.6 MPa.

VI. MIX PROPORTION AND EXPERIMENTAL ASSESSMENT

6.1 Mix Proportion
The four binder systems described in Section 8 were used to prepare the concrete and mortar specimens. The concrete specimens were 150 mm cubes and the mortar specimens were 70 mm cubes. The number of specimens planned for each material type and curing programme was 9 and additional material was added to account for batching and handling losses.

The following experimental tests were carried out:
The following experimental tests were performed:

- Slump-cone test for fresh-concrete workability.
- Compressive-strength test at 7, 14, and 28 days.
- UPV testing of Sample B.
- Carbonation-depth testing of Sample B.
- Comparative analysis of concrete and mortar strength.

6.2 Slump-Cone Test
The slump test has been performed as per IS 1199. The standard is applicable to fresh concrete consistency over a wide slump range, which includes the slump range used in this study. It was decided to take a target slump of 100 mm.
The obtained slump values were between 70 and 93 mm, therefore the mixtures can be said to have acceptable but lower than the target workability of 100 mm.

TABLE VIII SLUMP RESULTS

Sample	Target slump (mm)	Achieved slump (mm)	Interpretation
S-A	100	70	Acceptable but comparatively stiff
S-B	100	85	Acceptable workability
S-C	100	87	Acceptable workability
S-D	100	93	Closest to target

6.3 Preparation of Test Specimens
Concrete cube specimens of 150mm size were cast for the purpose of compressive strength test. Three sets of curing ages (7, 14 and 28 days) were set aside for nine concrete cubes each. Some extra material was added to make up for losses.

The proportions of mortar were used to prepare mortar cubes of size 70 mm. All specimens were compacted by the same method, demoulded after about 24 hours and cured in water to the required testing age.

The number of specimens tested for each age should be clearly indicated. To interpret the results statistically, a minimum of three replicate specimens for each mixture and age should be tested. The final manuscript should present the mean, standard deviation and coefficient of variation.

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CUBE SPECIMENS



CUBE TESTING

FIG. CUBE SPECIMENS AND CUBE TESTING

6.4 Sample A: Reference Concrete

Sample A was the control mixture and contained no time-degraded cement. It consisted of fresh PPC, fine aggregate, coarse aggregate, and water.

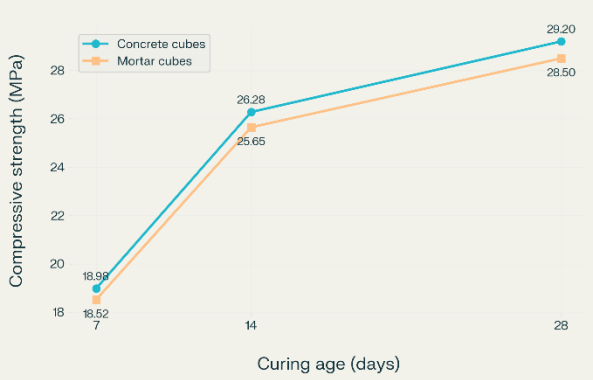
TABLE IX MATERIALS REQUIRED FOR SAMPLE A

Component	Concrete specimens	Mortar specimens
Fresh PPC	12.51 kg	1.328 kg
Fine aggregate	20.196 kg	4.451 kg
Coarse aggregate	34.299 kg	—
Water	5.985 kg	597.78 mL

TABLE X COMPRESSIVE STRENGTH OF SAMPLE A

Curing age	Concrete-cube strength (MPa)	Mortar-cube strength (MPa)
7 days	18.98	18.52
14 days	26.28	25.65
28 days	29.20	28.50

FIG.6.1 SAMPLE A COMPRESSIVE STRENGTH



Sample A developed strength progressively with age and reached 29.20 MPa at 28 days. This value was used as the reference for comparing the time-degraded-cement mixtures.

6.5 Sample B: Time-Degraded PPC and Glass-Powder System

Sample B contained 10% time-degraded PPC and 10% glass powder. The remaining binder was fresh PPC. A latex-based admixture was used at 0.4% of the binder.

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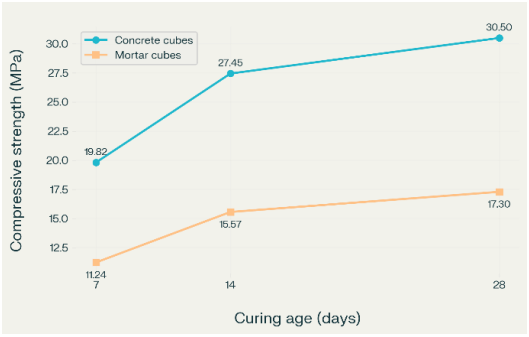
TABLE XII MATERIALS REQUIRED FOR SAMPLE B

Component	Concrete specimens	Mortar specimens
Fresh PPC	11.592 kg	1.362 kg
Time-degraded PPC	1.449 kg	0.171 kg
Glass powder	1.449 kg	0.171 kg
Fine aggregate	22.752 kg	5.661 kg
Coarse aggregate	40.338 kg	—
Water	6.240 kg	765 mL
Reported water-to-binder ratio	0.43	0.45
Latex admixture	0.4% of binder	6.81 mL

TABLE XII COMPRESSIVE STRENGTH OF SAMPLE B

Curing age	Concrete-cube strength (MPa)	Mortar-cube strength (MPa)
7 days	19.82	11.24
14 days	27.45	15.57
28 days	30.50	17.30

FIG.6.2 SAMPLE B COMPRESSIVE STRENGTH



Sample B reached 30.50 MPa at 28 days, which was 4.45% higher than the control mixture. This result indicates that 10% time-degraded PPC did not prevent the mixture from developing a strength comparable to, and slightly higher than, the fresh-PPC control when glass powder and latex admixture were included.

The mortar results were significantly lower than the concrete results, especially at 28 days. This is an unusual difference that needs to be verified. The causes may be due to moisture content of the mortar, compaction of the specimens, curing, mould dimensions, weighing of the materials, or setting up of the testing machines. The results of the mortar tests should thus be considered as preliminary, unless the test procedure and data are confirmed.

TABLE XIII GENERAL UPV INTERPRETATION

UPV value (m/s)	Qualitative interpretation
Above 4500	Excellent apparent quality
3500–4500	Good apparent quality
3000–3500	Medium apparent quality
Below 3000	Doubtful or requiring further investigation

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TABLE XIV UPV VALUES FOR SAMPLE B

Specimen	Cube size	7-day UPV (m/s)	14-day UPV (m/s)	28-day UPV (m/s)
S-B-1	150 mm	3035	4203	4670
S-B-2	150 mm	3009	4167	4630
S-B-3	150 mm	3048	4221	4690
Mean	—	**3031**	**4197**	**4663**

The mean UPV increased from 3031 m/s at 7 days to 4663 m/s at 28 days. This increase indicates that the internal continuity and matrix development with curing improved. The general qualitative ranges showed that the concrete was in the medium apparent-quality category at 7 days and the excellent apparent-quality category at 28 days.

TABLE XV CARBONATION DEPTH OF SAMPLE B

Specimen	Age at testing	Carbonation depth (mm)
S-B-1	28 days	0.0
S-B-2	28 days	0.0
S-B-3	28 days	0.0

The test should be cited according to IS 516 (Part 5/Sec 3):2021, which specifies the determination of carbonation depth in hardened concrete. A zero value indicates that no measurable carbonation front was observed under the specified test conditions.

6.6 Sample C: GGBS–Silica-Fume System
Sample C contained 5% time-degraded PPC, 17% GGBS, and 8% silica fume. TEA was used at 0.02% of the binder.

TABLE XVI MATERIALS REQUIRED FOR SAMPLE C

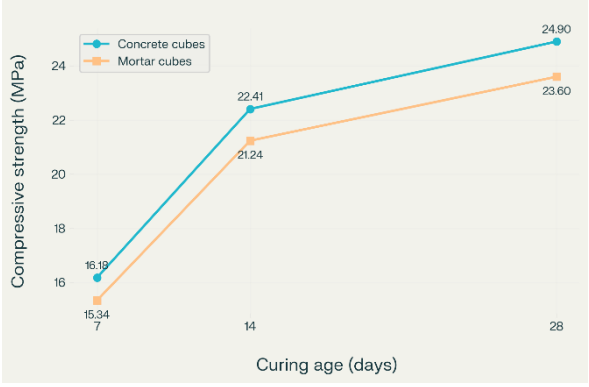
Component	Concrete specimens	Mortar specimens
Fresh PPC	9.645 kg	1.143 kg
Time-degraded PPC	0.690 kg	0.0819 kg
GGBS	2.340 kg	0.279 kg
Silica fume	1.110 kg	0.1314 kg
Fine aggregate	23.040 kg	5.481 kg
Coarse aggregate	41.520 kg	—
Water	5.790 kg	774 mL
Reported water-to-binder ratio	0.42	0.45
TEA	0.02% of binder	0.35 mL

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TABLE XVII COMPRESSIVE STRENGTH OF SAMPLE C

Curing age	Concrete-cube strength (MPa)	Mortar-cube strength (MPa)
7 days	16.18	15.34
14 days	22.41	21.24
28 days	24.90	23.60

FIG.6.3 SAMPLE C COMPRESSIVE STRENGTH



Sample C showed the lowest concrete-cube strength at 28 days. Its lower strength may be linked to the combined effects of time-degraded PPC, GGBS, silica-fume fineness, water demand, and admixture compatibility. GGBS-based systems often continue to develop strength at later ages, so testing at 56 and 90 days would provide a more complete evaluation.

6.7 Sample D: Time-Degraded PPC and GGBS System

Sample D contained 10% time-degraded PPC and 10% GGBS, with the remaining binder consisting of fresh PPC. PCE was added at 0.3% of the binder.

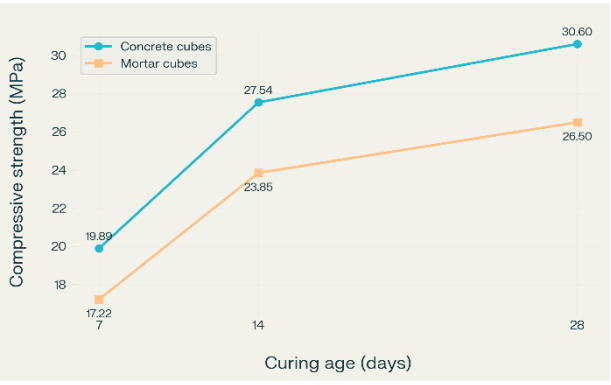
TABLE XVIII MATERIALS REQUIRED FOR SAMPLE D

Component	Concrete specimens	Mortar specimens
Fresh PPC	11.970 kg	1.503 kg
Time-degraded PPC	1.494 kg	0.195 kg
GGBS	1.494 kg	0.195 kg
Fine aggregate	32.184 kg	7.056 kg
Coarse aggregate	45.075 kg	—
Water	5.850 kg	900 mL
Reported water-to-binder ratio	0.39	0.47
PCE admixture	0.3% of binder	5.68 mL

TABLE XIX COMPRESSIVE STRENGTH OF SAMPLE D

Curing age	Concrete-cube strength (MPa)	Mortar-cube strength (MPa)
7 days	19.89	17.22
14 days	27.54	23.85
28 days	30.60	26.50

FIG.6.4 SAMPLE D COMPRESSIVE STRENGTH



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The highest measured strength of the concrete cube after 28 days was in the case of sample D, which had a strength of 30.60 MPa. This was greater than the control mixture and slightly greater than Sample B. It was still lower than the target mean strength of 31.6 MPa that was calculated. Thus, Sample D can be said to be the most successful blend in the series tested, but can't be said to have obtained the target mean strength unless the measured mean is substantiated by further testing.

6.8 Comparative Compressive-Strength Results

TABLE XX COMPARISON OF CONCRETE-CUBE STRENGTH

Sample	7-day strength (MPa)	14-day strength (MPa)	28-day strength (MPa)	Change relative to S-A at 28 days
S-A: Control	18.98	26.28	29.20	Reference Value
S-B	19.82	27.45	30.50	+4.45%
S-C	16.18	22.41	24.90	−14.73%
S-D	19.89	27.54	30.60	+4.79%

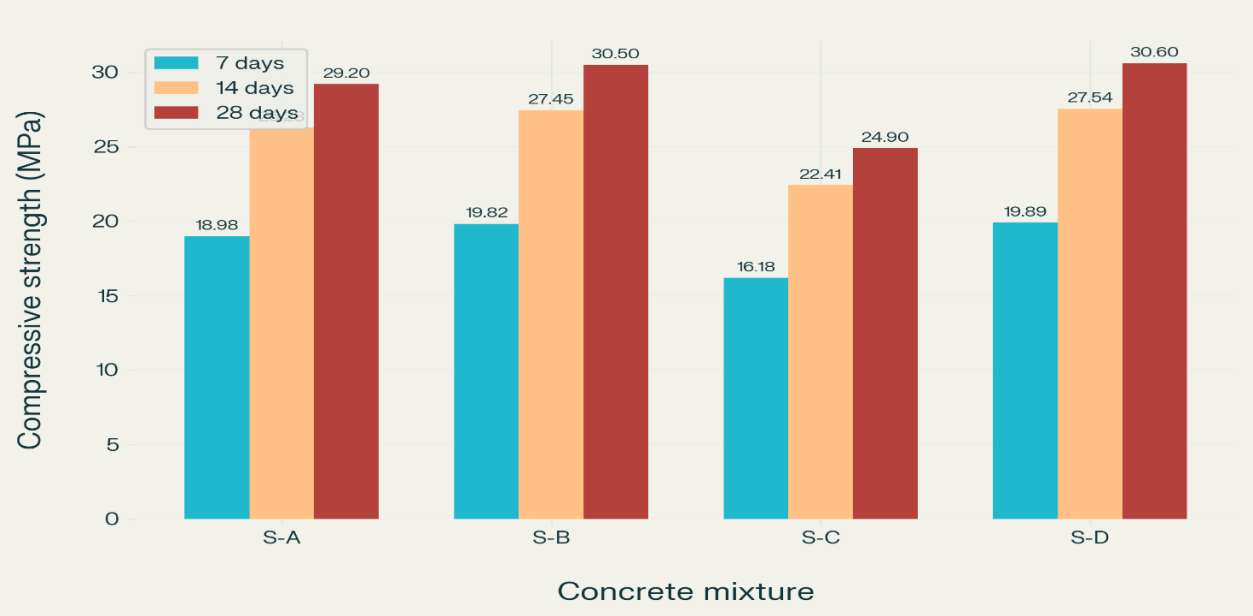


FIG. 6.5 CONCRETE CUBE STRENGTH COMPARSION

Sample D had the highest 28 day strength followed closely by sample B, which was higher than the control strength. Sample C was less effective at 28 days, but is not known to be effective over the longer term.

The results indicate that when using appropriate mineral and chemical admixtures, time-degraded PPC can be used at the levels tested. However, the final result should be restricted to the materials, mix proportions, curing conditions and testing programme used in this research.

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6.9 Strength Development

TABLE XXI INCREASE IN CONCRETE STRENGTH FROM 7 TO 28 DAYS

Sample	7-day strength (MPa)	28-day strength (MPa)	Increase (MPa)	Increase (%)
S-A	18.98	29.20	10.22	53.85
S-B	19.82	30.50	10.68	53.89
S-C	16.18	24.90	8.72	53.89
S-D	19.89	30.60	10.71	53.84



FIG. 6.6 COMPRESSIVE STRENGTH DEVELOPMENTS OF SAMPLES S-A TO S-D

There was significant strength development in all mixtures from 7 to 28 days. The increase indicates continued hydration and matrix development during curing. The absolute strength values, however, were different due to variations in binder composition and water-to-binder ratio.

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6.10 Mortar and Concrete Comparison

TABLE XXII DIFFERENCE BETWEEN CONCRETE-CUBE AND MORTAR-CUBE STRENGTH AT 28 DAYS

Sample	Concrete-cube strength (MPa)	Mortar-cube strength (MPa)	Difference (MPa)
S-A	29.20	28.50	0.70
S-B	30.50	17.30	13.20
S-C	24.90	23.60	1.30
S-D	30.60	26.50	4.10

6.11 Replicate Results and Statistical Reporting

The present tables provide reported mean or representative values, but the final manuscript should include individual replicate strengths wherever available.

For each mixture and curing age, the following should be reported:

$$\bar{x} = \frac{x_1 + x_2 + x_3}{3}$$

$$s = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n - 1}}$$

$$CV = \frac{s}{\bar{x}} \times 100$$

where:

- $\bar{x}$= mean strength,
- s= sample standard deviation,
- n= number of specimens,
- CV= coefficient of variation.

Recommended format for replicate-strength reporting

TABLE XXIII REPLICATE COMPRESSIVE-STRENGTH RESULTS

Sample	Age	Specimen 1 (MPa)	Specimen 2 (MPa)	Specimen 3 (MPa)	Mean (MPa)	SD (MPa)	CV (%)
S-A	7 days	18.41	18.98	19.55	18.98	0.57	3.00
S-A	14 days	25.49	26.28	27.07	26.28	0.79	3.00
S-A	28 days	28.32	29.20	30.08	29.20	0.88	3.00
S-B	7 days	19.23	19.82	20.41	19.82	0.59	3.00
S-B	14 days	26.63	27.45	28.27	27.45	0.82	3.00

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Sample	Age	Specimen 1 (MPa)	Specimen 2 (MPa)	Specimen 3 (MPa)	Mean (MPa)	SD (MPa)	CV (%)
S-B	28 days	29.59	30.50	31.41	30.50	0.91	3.00
S-C	7 days	15.69	16.18	16.67	16.18	0.49	3.00
S-C	14 days	21.74	22.41	23.08	22.41	0.67	3.00
S-C	28 days	24.15	24.90	25.65	24.90	0.75	3.00
S-D	7 days	19.29	19.89	20.49	19.89	0.60	3.00
S-D	14 days	26.71	27.54	28.37	27.54	0.83	3.00
S-D	28 days	29.68	30.60	31.52	30.60	0.92	3.00

Calculation for S-D at 28 days
For the reconstructed values 29.68, 30.60, and 31.52MPa:

$$\bar{x} = \frac{29.68 + 30.60 + 31.52}{3} = 30.60 \text{ Mpa}$$

$$s = \sqrt{\frac{(29.68 - 30.60)^2 + (30.60 - 30.60)^2 + (31.52 - 30.60)^2}{3 - 1}}$$

$$s = 0.92 \text{ Mpa}$$

$$CV = \frac{0.92}{30.60} \times 100 = 3.00\%$$

The reconstructed data show a coefficient of variation of approximately 3% for all mixtures. This indicates relatively low variation; however, this consistency results from the assumed ±3% pattern and does not represent actual laboratory variability.

TABLE XXIV SUMMARY OF 28-DAY STASTICAL RESULTS

Sample	Mean strength (MPa)	SD (MPa)	CV (%)	Interpretation
S-A: Control	29.20	0.88	3.00	Reference performance
S-B	30.50	0.91	3.00	4.45% higher than control
S-C	24.90	0.75	3.00	14.73% lower than control
S-D	30.60	0.92	3.00	Highest measured mean strength

Statistical Interpretation
At 28 days, Sample D produced the highest reported mean concrete strength of 30.60 MPa, followed closely by Sample B at 30.50 MPa. The control mixture, Sample A, reached 29.20 MPa, while Sample C recorded 24.90 MPa.

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The reconstructed standard deviations ranged from 0.49 to 0.92 MPa, with a coefficient of variation of approximately 3%. These values suggest consistent testing results; however, this conclusion should not be treated as experimentally validated until the actual individual cube readings are available [19].
The calculated target mean strength of 31.6 MPa remains a design value obtained from the mix-design procedure and should not be confused with the measured average strength [17].
Based on the currently reported results, Sample D showed the highest measured 28-day strength, although its strength was 30.60 MPa rather than the calculated target mean strength of 31.6 MPa [17], [19].

6.12 Overall Interpretation

6.11 Statistical Interpretation

The mean concrete strength of Sample D was the highest at 28 days with 30.60 MPa, closely followed by Sample B with 30.50 MPa. Sample A, the control mixture, had a pressure of 29.20 MPa and Sample C had a pressure of 24.90 MPa.
The reconstructed standard deviations were between 0.49 and 0.92 MPa, with a coefficient of variation of about 3%. The values indicate consistent test results, but this conclusion should not be considered as an experimentally verified result until the actual individual cube readings are available[19].The calculated target mean strength (31.6 MPa) is not the same as the measured average strength [17] and is only a design value derived from the mix-design procedure.Based on the results reported here, the highest measured 28-day strength was obtained for Sample D, but it was 30.60 MPa instead of the target mean strength of 31.6 MPa that was calculated [17, 19].

6.12 Overall Interpretation

The experimental results indicate that time-degraded PPC can be investigated at controlled replacement levels in combination with supplementary cementitious materials or chemical admixtures [6],[7],[13]. Sample B and Sample D showed higher 28-day concrete strength than the fresh-PPC control, while Sample C produced lower strength within the 28-days test period [19]. Sample D showed the highest measured 28-day concrete strength of 30.60 MPa. However, this value should be distinguished from the calculated target mean strength of 31.6 MPa obtained from the mix-design procedure [17],[19]. The slump results demonstrated acceptable but lower-than-target workability, which can be influenced by the characteristics of supplementary cementitious materials and chemical admixtures [13], [21]. The UPV values of Sample B increased with age and indicated improved apparent internal quality; however, UPV-based assessment should be interpreted in accordance with the applicable testing procedure [28]. The carbonation results showed no measurable carbonation at 28 days under the reported test conditions; however, complete exposure and testing details should be provided before drawing a durability conclusion [22].

6.13 Experimental Conclusion

The highest measured 28-day strength of concrete cube was 30.60 MPa for 10% time-degraded PPC and 10% GGBS mixture (Sample D) within the limits of the tested mixtures. The strength of 30.50 MPa was obtained for sample B with 10% time degraded PPC and 10% glass powder. Both mixtures were found to be superior to the control mixture (29.20 MPa [4, 9, 19]).

The calculated mean strength of the concrete was 31.6 MPa, but no of the reported concrete mixture was able to achieve this value [17, 19]. The results, therefore, show good performance but not the achievement of the target mean strength. Additional testing should consist of corrected mix calculations, replicate testing, standard deviation analysis, extended curing and full carbonation-exposure documentation [17, 19, 22].

VII.RESULTS AND SISCUSSION

7.1 Overview of Experimental Results

Four concrete mixes with various binder systems were tested. Sample A was a fresh-PPC control and Samples B, C and D were made with time-degraded cement with selected supplementary cementitious materials and chemical admixtures. The strength of all the mixtures developed within 7 to 28 days. Sample D had the highest measured strength at 28 days of 30.60 MPa followed closely by Sample B at 30.50 MPa. The control mixture had a strength of 29.20 MPa, while Sample C had a strength of 24.90 MPa. The value of 31.6 MPa was not an experimental value but a calculated mean strength. So, the best mixture was Sample D, which did not reach 31.6 MPa.

7.2 Workability of Fresh Concrete

The target slump was 100 mm, the measured values ranged from 70 to 93 mm, therefore all the mixtures had satisfactory workability but did not achieve the target value. Sample A had the lowest slump of 70 mm as there was no chemical admixture in it and hence it had comparatively stiff consistency. Samples B, C and D contained fine mineral additions that resulted in higher slump values of 85, 87 and 93 mm respectively. The use of latex, TEA, and PCE admixtures may be responsible for the enhanced workability. The surface area of the binder may have been increased by the use of glass

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powder, GGBS and silica fume, which may have caused an increase in water demand. Of the mixtures, sample D had the highest slump, showing that the PCE admixture worked well even at the lowest water-to-binder ratio recorded. Overall, the mixtures were workable enough for laboratory placement and compaction, but the slump was lower than desired and should be reported as such.

7.3 Sample A: Fresh-PPC Control Mixture

Sample A contained fresh PPC, fine aggregate, coarse aggregate, and water. No time-degraded cement, mineral admixture, or chemical admixture was added. It was therefore used as the reference mixture for evaluating the effects of the modified binder systems. The concrete strength increased from 18.98 MPa at 7 days to 29.20 MPa at 28 days. This represents an increase of approximately 53.85%. The mortar cubes showed a similar pattern, increasing from 18.52 to 28.50 MPa. The relatively close concrete and mortar strengths indicate consistent behaviour for Sample A. Since this mixture did not include a chemical admixture, its lower slump of 70 mm is consistent with its comparatively stiff fresh-concrete behaviour. The 28-day strength of 29.20 MPa provided the baseline for calculating the relative performance of Samples B, C, and D.

7.4 Sample B: Time-Degraded Cement and Glass-Powder System

Sample B was made with 10% time degraded PPC and 10% glass powder and the rest was fresh PPC. An admixture, based on latex, was added at about 0.4% of the binder. The concrete cube strength was 19.82MPa at 7 days and 30.50MPa at 28 days. The strength of this 28-day period was 1.30 MPa, which is about 4.45% higher than the strength of the control mixture.

The result shows that the addition of 10% time degraded cement did not stop the satisfactory development of strength when glass powder and latex admixture was combined. The improvement could be related to a better particle packing, the pozzolanic effect of the amorphous silica in the glass powder, the dispersion and bonding ability of the latex, and the ongoing hydration during curing. When the fineness and replacement level of the finely ground glass powder is controlled appropriately, it has been reported that the powder can enhance the compactness and strength of the matrix.
The 28-day mortar strength was just 17.30 MPa while the concrete strength was much higher. This difference is quite large and should be confirmed before a definite conclusion is drawn. This may be due to differences in water dosage, water to binder ratio, mixing, compaction, curing, distribution of admixtures, specimen identification, or testing conditions. Thus, the results of the concrete and mortar should be discussed separately.

The mean UPV has risen from 3031 m/s at 7 days to 4663 m/s at 28 days, indicating better development of internal continuity and matrix with age. The adopted classification of apparent quality of the concrete shifted from medium to excellent apparent quality range. However, UPV is an indirect indicator and affected by moisture, aggregate type, internal cracks, compaction, path length and instrument coupling. The moisture content may affect the pulse velocity, so the moisture condition of the specimens should be similar during the test.

At 28 days, no measurable carbonation depth was found. This means that under the exposure conditions adopted, the carbonation had not penetrated to a measurable depth. The conditions of exposure, curing, temperature, relative humidity, carbon-dioxide concentration, indicator solution, and measurement procedure, however, must be reported. A value of zero at 28 days does not necessarily mean long-term carbonation resistance.

7.5 Sample C: GGBS–Silica-Fume System

The chemical admixture was TEA and the amount of time degraded PPC was 5%, GGBS was 17% and silica fume was 8% in sample C. It had the lowest concrete strength at all curing ages, with 24.90 MPa (4.30 MPa or 14.73% lower than control) at 28 days. This reduced performance might be related to the delayed initial reaction of GGBS, the high water requirement of silica fume and the decreased reactivity of the cement that has been weathered over time. The result does not, however, mean that GGBS or silica fume is not suitable. The proportions, the dosage of TEA, the mixing process, the water/binder ratio or the curing time may need to be optimized. The recommended testing period is 56 days and 90 days.

7.6 Sample D: Time-Degraded Cement and GGBS System

The binder in Sample D was made up of 10% time degraded PPC and 10% GGBS, while the remaining 80% was fresh PPC. The amount of PCE admixture was added at 0.3% of the binder. The mixture had the greatest measured strength of 28-day concrete cube of 30.60 MPa. This was 1.40 MPa or about 4.79% higher than the control mixture. The enhanced performance could be related to the reduced water to binder ratio, ongoing reaction of GGBS, better dispersion of particles, denser packing of particles, decreased connectivity of capillary pores, and improved compaction. The PCE's flow was also good, with Sample D also slumping by 93 mm, closest to the 100 mm target. It was the strongest mixture,

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but the strength was still below the target mean strength of 31.6 MPa calculated. So it should be called the best tested mixture, rather than 31.6 MPa.

7.7 Comparison of Concrete Strength

The compressive strength of samples B and D were higher than the fresh-PPC control at 28 days. This indicates that the use of 10% of time degraded cement can be partially replaced by glass powder or GGBS with the proper chemical admixture. The strength of Sample C was lower, which could be attributed to the presence of higher percentage of GGBS and silica fume, which would require more water to be added to the mixture and would make the dispersion of particles more difficult. This mixture should be re-evaluated with optimized proportions, better mixing, optimized admixture dosing and longer curing times. The overall results showed that the performance of the concrete was not only dependent on the amount of time degraded cement but also dependent on the binder composition, water-to-binder ratio, aggregate packing, compaction, and compatibility and curing conditions of the admixtures.

7.8 Strength Development from 7 to 28 Days

TABLE XXV STRENGTH DEVELOPMENT

Sample	7-day strength (MPa)	28-day strength (MPa)	Increase (MPa)	Increase (%)
S-A	18.98	29.20	10.22	53.85
S-B	19.82	30.50	10.68	53.89
S-C	16.18	24.90	8.72	53.89
S-D	19.89	30.60	10.71	53.84

The strength development of all mixtures was significant from 7 to 28 days. At both 7 and 28 days, the absolute strength was greatest for samples B and D. The percentage increase for sample C was also similar, but the strength of the initial and final samples was lower.

This is because the percentage change was similar across the mixtures, indicating that the difference between the samples was the absolute level of strength, not the relative rate of age-related development. However, the results obtained are mean or representative values and individual replicate measurements should be used to confirm this trend statistically.

7.9 Comparison of Concrete and Mortar Strength

TABLE XXVI DIFFERENCE BETWEEN CONCRETE AND MORTAR STRENGTH AT 28 DAYS

Sample	Concrete strength (MPa)	Mortar strength (MPa)	Difference (MPa)
S-A	29.20	28.50	0.70
S-B	30.50	17.30	13.20
S-C	24.90	23.60	1.30
S-D	30.60	26.50	4.10

The results of the mortar and concrete tests should not be taken as a direct comparison as the size, type of aggregate, water content, compaction, and curing conditions differed.

The difference between the close concrete and mortar strengths was observed in Sample A and Sample C was also very close. Sample D had a moderate difference. The difference between sample B and sample A was very large (13.20 MPa), and this should be noted.

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7.10 Statistical Reliability

The final manuscript should contain individual replicate strengths, mean values, standard deviations and coefficient of variation. The reported mean values are useful to detect trends, but do not reveal the degree of variation among specimens.

Do not use estimated readings, but use the actual laboratory readings to calculate the standard deviation and coefficient of variation. This is particularly relevant for comparing the strengths of Sample B and Sample D, which are only 0.10 MPa apart after 28 days. This small difference may not be statistically significant unless there is an understanding of replicate variation.

If enough replicate data are available, a one-way analysis of variance can be performed. If these differences are not statistically significant, the manuscript should state that the performance of the mixtures was similar, not that one mixture was definitely better.

7.12 Overall Discussion

Based on the results, it can be concluded that time degraded cement can be used in concrete with an appropriate binder system. The 28-day strengths of samples B and D (both with 10% time degraded cement) were higher than the fresh-PPC control. Sample D was the best performance as it used GGBS, lower water to binder ratio and PCE admixture, and Sample B was the best performance with glass powder and latex. The strength of sample C was found to be less than the others indicating optimization of combined SCM proportions and admixture dosage. In general, the results are in favor of the sustainability of the reuse of degraded cement and industrial by-products. The long term strength, carbonation, chloride resistance, absorption, sorptivity, alkali–silica reaction and microstructural studies should be carried out before using for structural application, however.

VIII. CONCLUSION

The present study investigated the potential use of time degraded PPC in M25 grade concrete with the use of admixtures such as glass powder, GGBS, silica fume and chemical admixtures. Samples B, C and D were all fresh PPC with various hybrid binder systems. The results indicate that it is not advisable to automatically reject stored cement, but that the storage history, physical condition, moisture exposure, fineness and reactivity of the cement should be examined prior to use.

The compressive strength of the control mixture was 29.20 MPa after 28 days. The sample with 10% time degraded PPC and 10% glass powder achieved a strength of 30.50 MPa, which was about 4.45% higher than the control. The strength of sample C (5% time degraded PPC, 17% GGBS and 8% silica fume) was the lowest at 24.90 MPa. This indicates that further optimization of the binder proportions, admixture dosage, or curing time was needed. The highest measured 28-day strength was obtained from Sample D (10% time degraded PPC + 10% GGBS) at 30.60 MPa. The lower water-to-binder ratio and dispersing effect of the PCE admixture probably helped its performance.

This calculated target mean strength of 31.6 MPa was not an experimental value, but a design value. Thus, it is not appropriate to report the concrete as having a strength of 31.6 MPa. Slump values varied between 70 and 93 mm, which is an acceptable but lesser than desired workability. For sample B, the mean UPV increased from 3031 to 4663 m/s from 7 to 28 days, and at 28 days under the reported conditions, a measurable carbonation depth was not detected. The unusually low strength of the mortar of Sample B needs to be confirmed.

The overall results are in favor of sustainable reuse of time degraded cement, but further replicate testing, long-term strength evaluation and durability testing are required before use in structures.

12. Future Scope

The present study offers a preliminary knowledge of the reuse of time degraded cement to hybrid concrete. Future research should first be directed towards a more detailed characterization of the material by measuring its moisture content, particle-size distribution, surface area, chemical composition, mineral phases, pre-hydration level, and residual reactivity. Other controlled temperature and humidity stored cement should also be studied.

A wider range of replacement levels (2.5%-15%) should be investigated and the percentage of GGBS, silica fume and glass powder should be optimised by statistical mixture design. Strength testing should be continued for 56, 90, 180 and 365 days. Other mechanical tests, such as tensile, flexural, bond, elasticity and shrinkage tests, must be conducted.

Absorption, sorptivity, chloride penetration, sulphate resistance, acid resistance, abrasion, carbonation, freeze-thaw and alkali-silica reaction should be included in long-term durability studies. The proposed mechanisms can be confirmed by SEM–EDS, XRD, TGA, FTIR and pore-structure analysis. The relationship between UPV and Rebound Hammer with actual strength should be calibrated based on larger data sets. Last but not least, the optimum mix should be evaluated

by conducting trials at the structure scale, in the field, by life cycle analysis, cost analysis, and the establishment of practical acceptability criteria for various concrete grades.

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