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Original Article

Mechanical and Microstructural Performance of M30 Grade Sustainable Concrete with Dolomite Powder and Sugarcane Bagasse Ash as Blended Cement Replacements

Dhanamma Palsam[1], Murugan. R[2], Manohar. G[3]

[1,2]*Department of Civil & Structural, Annamalai University, Tamil Nadu, India.*
[3]*Department of Civil Engineering, Matrusri Engineering College, Hyderabad. Telangana, India.*

[1]*Corresponding Author : palsamdhanamma@gmail.com*

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Abstract - *This study analyzes the combined effects of dolomite powder (DP) and Sugarcane Bagasse Ash (SCBA) used as a binary auxiliary binding composition on M30 grade concrete to enhance its mechanical behavior, durability, and microstructure stability when subjected to aggressive environment conditions. Five different concrete specimens have been fabricated using replacement rates varying from 0% to 30% for DP and SCBA mixture ratios. The experimental studies consist of compressive strength, flexural strength, stress-strain relationship, Elastic Modulus, water absorption, chemical durability during acid attack, and X-ray diffraction (XRD) phase investigation. It was observed that specimen M3 with 10% DP and 5% SCBA mixture attained the maximum values of 28 days compressive strength as 47.84 MPa, flexural strength as 4.84 MPa, Young's modulus as 17400 MPa, and the minimum value of water absorption as 3.52%.*

Keywords - *Dolomite powder, Sugarcane bagasse ash, Sustainable concrete, Durability performance, and X-ray diffraction.*

1. Introduction

The growing environmental load related to Portland cement manufacturing has led to more studies on supplementary cementing materials that can reduce the usage of clinkers while still ensuring their effectiveness. Agricultural and mineral waste products appear to be viable substitutes thanks to their ability to react chemically, serve as fillers, and help develop circular construction. Among them, sugarcane bagasse ash (SCBA) and dolomite powder (DP) seem to hold promise for binary addition to concrete mixes owing to their synergic hydration properties and sustainability [1, 2, 3].

1.1. Background to Sugarcane Bagasse Ash in Cement Matrixes

The utilization of Sugarcane Bagasse Ash (SCBA) as a supplemental binding compound is a topic of great interest due to its capability to increase the performance and sustainability of concrete. Owing to high amounts of amorphous silica in SCBA, secondary pozzolanic reactions take place in concrete, which produce more gel of calcium silicate hydrates, thus making the matrix denser. It also has the advantage of having a small particle size that leads to better particle packing and reduced permeability. Thus, concrete made with an appropriate amount of SCBA shows higher compressive strength, better chloride penetration resistance, and increased durability. [4, 5]. This positive effect largely depends on the calcination temperature, fineness, and amount of SCBA replacement in cement matrices [6, 7]. Several studies have found that moderate use of SCBA enhances mechanical efficiency by promoting the formation of calcium silicate hydrates, while high doses cause dilution and inhibit hydration at an early age [8, 9]. Modern studies have also indicated that effective doses of SCBA provide long-term durability in sulphate and acidic conditions due to the densification of pores and matrix discontinuities [10, 11].

1.2. The Contribution of Dolomite Powder in Concrete Matrix Improvement

The primary role of dolomite powder is to act as a filler material and a nucleation medium for cement-based matrix materials. The calcium carbonate portion of dolomite enhances the interfacial zone structure and improves the early age stiffness characteristics, especially at moderate substitution rates [12, 13]. The presence of dolomite powder in a blend system is known to improve the workability and densification of the hydration products through dense microstructure formation. In addition, the filling effect provided by the dolomite particles limits capillary porosity and facilitates proper stress transfer in hydrated cement paste [14, 15]. Nevertheless, an increase beyond a certain limit may limit the clinker quantity, resulting in lower strength.

1.3. Synergistic Possibilities of Combined DP and SCBA Application

A synergy can be created by using dolomite powder and sugarcane bagasse ash, whereby dolomite powder offers an immediate enhancement in particle packing efficiency, whereas SCBA can provide delayed pozzolanic activity. The binary combination could enhance the hydration process by increasing nucleation rate as well as producing further CaS hydrogel products [17, 18]. Studies show that two-component additives may work better than single-component additives due to physical filling and chemical reaction happening simultaneously. In two-component additives, fillers increase the denseness of the mineral phase; meanwhile, silica ash reacts with free calcium hydroxide, decreasing weak crystals and increasing the strength of the hydrated phase [19, 20].

1.4. Durability and Mechanical Research Gap

Despite the vast literature on the subject, research on the use of SCBA has been focused solely on it as a standalone supplementary cementitious material, but there is scant literature concerning the comprehensive evaluation of binary systems of dolomite powder and SCBA when subjected to mechanical load, elasticity, chemical durability, and phase transformation analysis. Most research studies only deal with compressive strength testing or chemical durability alone without incorporating aspects of stress/strain analysis, calculation of the elastic modulus, water absorption, and x-ray diffraction analysis of phases [21, 22]. Past studies have highlighted the distinct possessions of SCBA and dolomite powder on certain engineering properties of cement-based composites; however, there is a shortage of studies that have addressed their binary usage.

In structural-grade concrete. Literature reports available thus far have mostly addressed compressive strength, fresh concrete properties, or individual aspects of durability, whereas more integrated studies addressing mechanical properties, stress-strain relationship, elastic modulus, water absorption, chemical resistance, and microstructure formation have been relatively ignored.

Additionally, the optimum binary dosage required to achieve the desired improvements in strength, durability, and hydration properties in M30 concrete have not been determined. Thus, the current study aims to fill this gap through an experimental investigation including mechanical, durability, and XRD analysis for a better insight into the engineering properties of binary dolomite powder and SCBA blended concrete [1, 3, 4, 7, 10, 13, 15, 17, 18, 20, 23].

1.5. Objective and Novelty of the Current Work

In This research work objective to find the visual characteristics of M30 concrete having dolomite powder and bagasse ash from sugarcane as dual admixtures in a composite form. Five samples were prepared in which increasing amounts of dual admixtures were used, and their compressive strength, flexural strength, stress-strain response, elasticity, acid attack resistance, water absorption, and XRD analysis were studied. The key novel point of this research is to find out the optimal proportion for dual admixture that will be able to improve mechanical properties while reducing permeability and increasing chemical resistance of the resulting products.

1.6. Engineering Importance and Research Rationale

The raising pressure on sustainable construction materials has directed to innovations in green cement composites that can limit environmental impact without affecting the properties of the material. The utilization of industrial and agricultural by-products as partial cement substitutes provides a solution to reduce cement usage, manage landfill waste, and decrease carbon dioxide emissions in cement manufacturing processes. Such technology not only conserves resources but also promotes the sustainability of concrete using waste materials that need to be managed [19, 20]. Despite the good engineering requirements of the auxiliary binding compounds, the practical implementation of the materials in the production of structural concrete needs further research in mechanical and durability loading. Therefore, studying the interaction of dolomite powder and sugarcane bagasse ash is vital for creating durable and sustainable concrete [21, 22].

1.7. Contributions to Practical Research

In this research work, a thorough examination of the binary cement replacement with dolomite powder and sugarcane bagasse ash in M30 grade concrete is conducted by means of mechanical, durability, and microstructural tests. As opposed to previous works dealing mostly with single materials and performance factors, this paper combines compressive strength, flexural strength, stress–strain relationship, elastic modulus, water absorption capacity, chemical resistance, and X-ray diffraction test [16, 18]. Thus, the results of this investigation provide the optimum replacement ratio that contributes to the manufacturing of sustainable constructional concrete with enhanced technical characteristics and effective reuse of waste products [19, 24].

2. Literature Review

The usage of auxiliary binding compounds in concrete mixes has come a long way from a mere clinker substitution approach to the performance-based approach, which involves the improvement in efficiency of the hydration process and sustainability. Agricultural waste and carbonate mineral additives have been used extensively, as not only do they help in the disposal of industrial waste but improve the engineering properties of cementitious composites. Out of these, the Sugarcane Bagasse Ash (SCBA) is a highly reactive pozzolanic material that helps in developing secondary hydrations, while the dolomite powder (DP) acts mainly as filler material. The use of both these materials together can provide an opportunity to produce green concrete, having improved mechanical and durability properties with improved microstructure.

2.1. Development of SCBA-based Concrete Mixtures

There has been various research done regarding the use of SCBA as a cement substitute owing to its highly amorphous silicon content and reactivity with calcium hydroxide formed during hydration of the cement [3, 4]. Research revealed that finely ground SCBA can improve the compressive strength of concrete by forming secondary calcium silicate hydrates at less than 15% of the amount of replacement [3, 4].

It was also found out that the effectiveness of SCBA greatly depends on the quality of combustion, degree of grinding, and amount of carbon present in the material [5, 6]. The binary systems composed of SCBA and limestone-based materials were found to exhibit better stability during hydration because the carbonate-based fillers have nucleation sites that help in the rapid hydration process, while SCBA promotes densification through pozzolanic reactions in the long run [7, 8].

2.1.1. Bagasse Ash from Sugarcane in Cementitious Systems

Due to its high amount of silica content and availability as a by-product in many tropical countries, Sugarcane Bagasse Ash has gained a lot of research interest as a replacement for cement. According to de Siqueira and Cordeiro, binary and ternary cement systems containing SCBA were effective in improving the efficiency of hydration, resulting in additional amounts of C-S-H gel when the replacement was maintained within moderate limits [13].

SCBA-based cement systems have been effective in improving durability characteristics, as sorptivity was reduced and pore connectivity was minimized [14]. They observed that processed SCBA has been effective in improving compressive strength and chloride resistance due to enhanced secondary hydration [15]. In addition, microstructural densification was highly pronounced when SCBA was used with supplementary binders rich in silica content, as confirmed [16]. The processing SCBA has been effective in improving mechanical consistency and minimizing variability in concrete systems [17].

2.2. Mechanical Performance Trends in SCBA Blended Concrete

Several studies have found that medium-level SCBA blending enhances compressive strength and flexural resistance due to increased densification of hydrates and decreased pore connectivity. The experimental results show that a 5 to 10% substitution of SCBA yields an optimal mechanical performance due to adequate silica content and low calcium hydroxide production [9, 10]. Increased substitutions result in reduced strengths since the dilution effect of cement dominates pozzolanic gain. The trend is especially significant during early-age curing, where hydration rates depend on the clinker rate [11, 12]. Investigations into the ternary mixture showed that mechanical enhancement was higher when combining SCBA with highly active mineral fillers [13, 14].

2.3. Behavior of SCBA-Concretes Under Aggressive Conditions

Durability has become an essential factor in the evaluation of SCBA concrete mixes due to the direct influence of microstructure on permeability and chemical resistance properties. Experimental studies have shown that appropriate optimization of the SCBA content leads to significant reductions in strength losses owing to the formation of less permeable structures and a barrier for aggressive ions' penetration into concretes [15, 16].

Additionally, sulphate resistance experiments have proven that SCBA concretes possess higher resistance to expansion thanks to decreased amounts of calcium hydroxide and increased hydration network density [17, 18]. Resistance to acidic attacks is achieved because of the secondary hydration products, which decrease free lime [19].

2.4. Interpretation from Mineralogical Aspects and XRD Findings

The significance of X-ray diffraction cannot be overstated when it comes to analyzing the hydration behavior of SCBA concrete. Commonly observed data for such systems include lower intensity of portlandite with higher quartz and calcite intensity, proving the pozzolanic reactions are indeed ongoing [20]. Systems that employ carbonate-bearing materials can exhibit enhanced calcite phase stability with hydration amorphous broadening, which signifies better packing structure within the hydrated paste [21]. UHPC and blended concrete systems utilizing SCBA have been found to exhibit lower crystallinity of calcium hydroxide due to extended silica reactivity during hydration, proving improved hydration maturity [22]. Comparing the mineralogical findings of SCBA and fly ash showed how effective SCBA can be as pozzolanic material for concrete [23].

2.5. Recognized Research Gap

The available literature proves the individual advantages of SCBA and mineral fillers, there is a paucity of systematic studies on binary blends of dolomite powder and SCBA subjected to combined loading, stress-strain behavior, elastic modulus measurement, multiple acid resistance testing, water absorption, and X-ray diffraction analysis for M30 grade concrete. Majority of published works have focused on strength characteristics alone, whereas holistic mechanical, durability, and mineralogical studies are inadequately explored.

2.6. Critical Analysis of Existing Literature

The latest literature has repeatedly shown that incorporation of SCBA in cementitious composites enhances their mechanical properties and durability due to pozzolanic activity and ability to refine pores [1, 3, 6]. In addition, there has been an improvement in hydration process and aggressiveness resistance in case of binary and ternary systems with SCBA [7, 14, 20].

Nevertheless, while most recent literature has focused on compressive strength or durability of the material only, very little literature exists regarding comprehensive assessment of mechanical properties, stress–strain behavior, elastic modulus, chemical durability, and microstructure evaluation.

The interaction between dolomite powder and SCBA is still unexplored in structural grade M30 concrete, which opens a wide research area towards sustainable blended cements development [15, 17, 23].

2.7. Research Challenges

The great strides have been made in sugarcane bagasse ash as a supplementing binding compound; there are still some key research issues that need to be addressed. Most of the current research deals solely with the substitution of one material or focuses on the analysis of a few selected engineering properties.

Therefore, there is an inadequate amount of knowledge available regarding the combined effect of agricultural and mineral supplementing materials.

Specifically, there is a lack of analysis that combines mechanical properties, durability, and microstructure of binary blends. [10, 13]. Moreover, the issues of durability in aggressive environmental conditions, statistics validation of experiments, and microstructure correlations are poorly developed [12, 20].

Such problems hinder the practical use of binary systems of cement and make it necessary to find an integral approach that will allow us to evaluate different criteria simultaneously [16, 18, 21].

2.8. Contributions to Research by the Present Study

The present study contributes to the existing research gaps through carrying out an elaborate experimental investigation of the M30 concrete with binary dolomite powder and sugarcane bagasse ash as a substitution compound for cement.

This study differs from other studies, which have mostly concentrated on compressive strength or any particular durability test, in that the study evaluates M30 concrete with binary dolomite powder and sugarcane bagasse ash with respect to compressive strength, flexural strength, stress-strain characteristics, elastic modulus, water absorption, chemical resistance under various environmental exposures, and x-ray diffraction analysis.

Moreover, the study determines the optimal binary replacement ratio that can enhance the engineering performance of the composite material while ensuring sustainable use of industrial and agricultural wastes.

A detailed review on current studies carried out by utilizing Sugarcane Bagasse Ash (SCBA) as a concrete material is Provided in Table 1 below, where the main results obtained in previous studies and their limitations are identified.

Earlier studies have revealed that the addition of SCBA in suitable percentages improves mechanical performance, durability, hydration process, and microstructure development of cementitious materials.

Such effects can be accredited to pozzolanic activity of SCBA, which results in higher calcium silicate hydrate generation, pore structure modification, and concrete impermeability. Hence, better environmental exposure resistance was also achieved. Although promising results were obtained, studies related to the combined use of SCBA and dolomite powder in high-strength concrete have not been conducted yet.

Especially the studies that involve mechanical properties, durability, stress–strain relation, elastic modulus, and microstructure assessment together are very rare. Therefore, the need for conducting current research is quite evident.

3. Materials and Methods

To assess the impact of the addition of DP and SCBA as cementing agents in the M30 grade of concrete, concrete specimens were prepared and analyzed in the lab. The applicable Indian Standard codes were strictly followed in the entire process.

The general methodology employed for the preparation of M30 grade sustainable concrete with the use of dolomite powder and sugarcane bagasse ash as binary replacements of cement is shown in Figure 1.

The study began with the selection, preparation, and characterization of the raw materials, followed by the designing of concrete mixes with various percentages of replacement. Fresh concrete samples were produced, poured into standard moulds, and tested for mechanical performance after being subjected to HYDRATION. The mechanical evaluation of the concrete was accomplished in terms of strength testing, while the durability test involved water absorption and chemical resistance.

Table 1. Summery of literature review

Ref.	Author(s)	Material / Study Focus	Major Findings	Research Gap Identified
[1]	Abdalla et al. (2024)	SCBA concrete durability review	SCBA improves strength and durability under	No binary dolomite–SCBA evaluation under combined
[2]	Abdalla et al. (2022)	Eco-friendly SCBA concrete	Moderate SCBA improved compressive strength	Elastic modulus and stress–strain not studied
[3]	Abdalla et al. (2022)	SCBA and silica fume concrete	High-volume SCBA improved durability	Binary mineral filler interaction absent
[4]	Amin et al. (2022)	High-volume bagasse ash concrete	Microstructure improved with silica-rich ash	Dolomite-based nucleation effect not examined
[5]	Chen et al. (2023)	Calcined SCBA mortar	Chloride resistance improved significantly	No structural grade concrete analysis
[6]	da Silva et al. (2021)	SCBA concrete durability	Pore refinement improved durability	No stress–strain modelling
[7]	de Siqueira and Cordeiro (2022)	SCBA and limestone blends	Binary blends improved hydration	is specifically not investigated
[8]	El-Said et al. (2022)	Raw and processed SCBA concrete	Processed ash enhanced strength	Acid durability not been comprehensively evaluated
[9]	Farrant et al. (2022)	SCBA with silica fume	Mechanical and durability improved	XRD phase comparison limited
[10]	Francioso et al. (2024)	SCBA valorization	Sustainable binder potential confirmed	Structural performance under binary replacement is lacking
[11]	França et al. (2023)	SCBA clinker replacement	Feasible clinker reduction	Mechanical optimization incomplete
[12]	Gupta et al. (2023)	SCC with SCBA	Durability improved	Conventional M30 concrete not studied
[13]	Iqbal et al. (2024)	SCBA composites	Cementitious performance improved	No dolomite synergy studied
[14]	Jittin and Bahurudeen (2022)	SCBA ternary systems	Rheology improved	Elastic modulus absent
[15]	Khalil et al. (2021)	SCBA review	Strong pozzolanic potential established	Binary hybrid systems underexplored
[16]	Khamput et al. (2025)	SCBA and stone dust	Strength increased at optimum dosage	Mineralogical mechanism incomplete
[17]	Kolawole et al. (2021)	State-of-the-art SCBA review	Broad SCBA applications identified	Combined durability and XRD gap remain
[18]	Liu et al. (2024)	Ternary SCM design	Environmental benefit confirmed	Dolomite-based binary structural system is absent
[19]	Memon et al. (2022)	Processed SCBA concrete	Mechanical properties improved	Stress–strain relationship absent
[20]	Subhani et al. (2024)	Binary/ternary/quaternary SCBA blends	Strength improved in blended systems	No detailed modulus evaluation
[21]	Talukdar et al. (2025)	SCBA binder systems	Fresh and mechanical properties optimized	Durability under acid exposure limited
[22]	Wu et al. (2022)	UHPC with SCBA	Ultra-dense microstructure achieved	Normal strength concrete application is limited
[23]	Zhang et al. (2020)	SCBA characterization	SCBA comparable to fly ash	Binary dolomite interaction absent

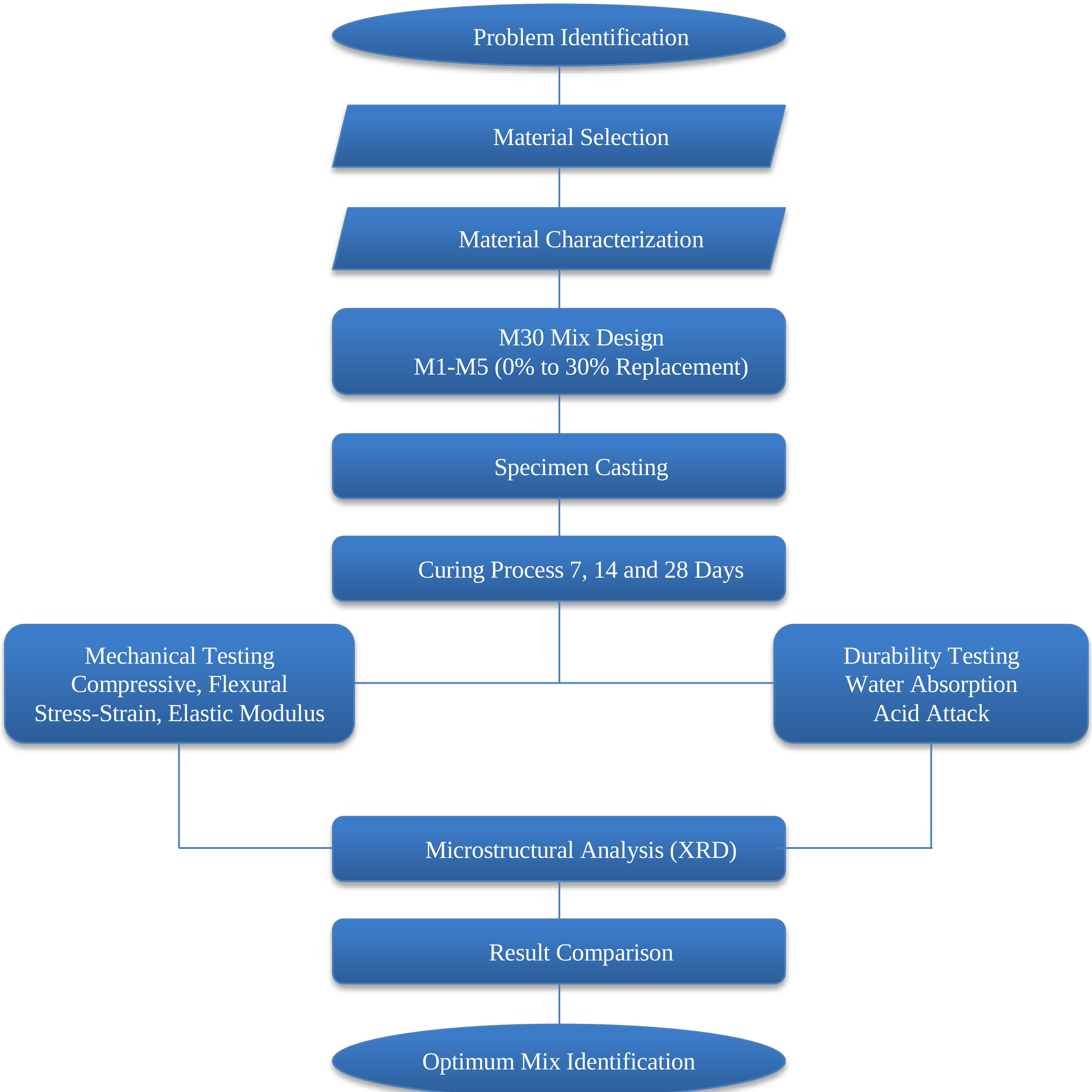

Fig. 1 Methodology flow chart for sustainable concrete using dolomite powder and sugarcane bagasse ash

3.1. Constituent Composition

The main binder material for all concrete mixtures was Ordinary Portland Cement (OPC) grade 53, which met BIS criteria. Natural river sand that met Zone II gradation standards and went through a 4.75mm filter was utilized as fine aggregate, while crushed angular material with a maximum size of 20mm was used as coarse aggregate.

Potable water, free of impurities and dangerous compounds, was used to build the concrete mix. Dolomite powder was employed as a mineral filler material because of its small particles and calcium carbonate content. Sugarcane bagasse ash was employed as supplemental cementitious material due to its presence of high reactive silica in its conformation.

3.1.1. Material Characterization

To ensure the uniformity and reliability of the trials, all cementitious additional materials utilized in the investigation were thoroughly evaluated before mixing. Sugarcane Bagasse Ash (SCBA) came from a local sugar mill. The material was dried, ground, and sieved for achieving the proper size of particles that could be added to the concrete mixture. The dolomite powder (DP) was supplied from a mineral processing company and kept under laboratory storage conditions. The physical properties of the materials (specific gravity, fineness, bulk density, moisture content) were tested using the standard methods. The visual characteristics of Portland Pozzolana Cement (PPC) were ascertained based on the provisions of **IS 4031 (Parts 1, 2, 4, and 11) **. Physical parameters such as consistency, specific gravity, initial setting time, and bulk density were tested to establish whether the cement is suitable for construction purposes. Results of the tests conformed to the specifications laid out in **IS 1489**, thus establishing that the quality of cement utilized in this study was of a good level. Specific gravity, bulk density, and fineness of the dolomite powder were tested as per **ASTM C188** and **ASTM C29** accordingly. Dolomite powder was chosen because of its fine grain size, low moisture content, and desirable physical properties.

Table 2. Measured physical characteristics of cement used in the concrete mixture

S. No.	Parameter	Observed Value
1	Normal consistency	30%
2	Specific gravity	3.14
3	Initial setting time	30 min
4	Fineness	4.44%
5	Bulk density	1.44 g/cc

The visual characteristics of sugarcane bagasse ash (SCBA), like specific gravity, bulk density, fineness, moisture content, and physical appearance, have been identified through ASTM C188 and ASTM C311 methods. Special emphasis has been laid on moisture content control as it owns a significant part in measuring the exact quantity of water required in the concrete mixture. Fine particle size and low specific gravity of SCBA aid in better particle packing, which can be utilized as an auxiliary binding compound. Moreover, the physical properties of fine and coarse aggregate like specific gravity, bulk density, and fineness modulus, have been identified using IS 2386 (Part 1 and Part 3). It was found out from the results that the aggregates meet the required conditions and can be used to make concrete mixes.

Table 3. Physical characteristics of dolomite powder used in the study

S. No.	Parameter	Observed Value
1	Consistency	30%
2	Specific gravity	3.14
3	Initial response time	30 min
4	Fineness	4.44%
5	Bulk density	1.44 g/cc

The physical properties of dolomite powder are presented in Table 3. The specific gravity of the material was 3.14, the bulk density was 1.44 g/cc, consistency was 30%, initial response time was 30 minutes, and fineness was 4.44%.

Fig. 2(a) Dolomite Powder

Fig. 2(b) Sugarcane Bagasse Ash.

Fig. 2 below displays the supplementary cementitious materials used in this investigation. The dolomite powder in Fig. 2(a) was used as a mineral filler, while the sugarcane bagasse ash in Fig. 2(b) It was established that the bulk density of the ash was 0.68 while the specific gravity of the ash was 2.6. This proved that the ash had a lower weight compared to the cementitious materials. The carbon content in the ash had a black colour and fineness of 10%. The percentage of moisture in the ash was 16%.

Table 4. Physical characteristics of sugarcane bagasse ash

S. No.	Parameter	Measured Value
1	Specific gravity	2.6
2	Bulk density	0.68 g/cc
3	Fineness	10%
4	Colour	Black
5	Moisture content	16%

The physical properties of the fine aggregate are enumerated in Table 5. The analysis shows that the fine aggregate met the Zone II gradation criteria, having a fineness modulus of 2.53, which is ideal for concrete formation. The bulk density of 1.70 g/cm³ is indicative of proper packing of particles to produce concrete, while the specific gravity of 2.63 is within the acceptable limits set for natural fine aggregate. This confirms the selection of the fine aggregate having appropriate physical properties for producing the concrete mixtures.

Table 5. Physical properties of fine aggregate

S. No.	Parameter	Observed Value
1	Fineness modulus	2.53
2	Specific gravity	2.63
3	Bulk density	1.7 g/cc

Table 6 shows an overview of the physical properties of the coarse aggregate material, as measured. With a modulus of fineness of 7.57, it was appropriate to produce concrete mixtures. In addition, the density of the aggregate was verified to fall within the acceptable range for use in construction works by a specific gravity of 2.61. On the other hand, a bulk density of 1.57 g/cc verified its acceptable packing characteristics for making concrete mixtures.

Table 6. Physical properties of coarse aggregate

S.	Parameter	Observed Value
1	Fineness modulus	7.57
2	Specific gravity	2.61
3	Bulk density	1.57 g/cc

3.2. Mix Proportions

Bureau of Indian Standards' rules were observed in proportioning the M30 concrete mixture. The proportions of cement, fine aggregate, coarse aggregate, and water for control mixture were 1:1.48:2.68:0.43, respectively. Dolomite powder and sugarcane bagasse ash were added in specific amounts to replace cement in the mixture.

3.2.1. Rational for Choosing the Binary Replacement Levels

Dolomite powder and sugarcane bagasse ash were chosen at certain replacement levels with an objective of studying the significance of cement replacement on the behavior of M30 grade concrete. The four different replacement levels were considered to study the transition from lower to higher amounts of the additives used, along with maintaining sufficient workability and structural stability. The lower amount of the replacement levels was used to improve hydration and packing of particles. Higher replacement levels were considered to find the maximum level beyond which the strength could be reduced due to dilution of the cement.

Table 7. Description of blended concrete mixes used in the experimental program

S. No.	Mix ID	Mix Description
1	M1	Control M30 concrete mixture without cement replacement
2	M2	M30 concrete containing 5% Dolomite powder and 2.5% Sugarcane bagasse ash as partial cement substitutes
3	M3	M30 concrete containing 10% dolomite powder and 5% sugarcane bagasse ash as partial cement substitutes
4	M4	M30 concrete containing 15% dolomite powder and 7.5% sugarcane bagasse ash as partial cement substitutes
5	M5	M30 concrete containing 20% dolomite powder and 10% sugarcane bagasse ash as partial cement substitutes

3.3. Preparing and Curing Specimens

Several studies have shown that the use of coal mine overburden materials will affect fresh concrete and hardened concrete properties according to the level of replacement and type of particles used. The use of overburden sand in cement mortars has been proven to exhibit adequate strength development [11], whereas concrete mixes using overburden waste rocks have proven to be resistant to. Before the gradual addition of water until the required workability was achieved, dry mixing was done to ensure the uniform distribution of all the elements present.

Prism specimens of 100mm x 100mm x 500mm were prepared for the measurement of flexural strength, whereas cube specimens measuring 150mm x 150mm x 150mm were prepared for the measurement of compression strength as well as durability. After the specimens were cast, they were left for a day before they were removed from the mold for curing at room temperature water [24].

3.3.1. Number of Specimens and Experimental Replication

For the validation of the results obtained from experiments, several specimens were prepared and tested for each type of concrete mixture. Cube specimens were constructed to test concrete's compressive strength and durability, prism specimens for flexural strength, and cylindrical specimens for stress-strain and elastic modulus. All specimens were prepared in similar laboratory conditions following the same procedure of mixing, casting, and curing the specimens. The values presented in this paper are the average values from several experiments.

3.4. Conditions of Testing

All experiments were carried out under laboratory conditions to achieve consistency in the entire testing process. Fresh concrete was prepared by following the same procedure in all batches, then cast into standard molds and allowed to cure in clear water up to the required testing age. Mechanical testing was carried out using standardized testing equipment, while durability testing was conducted by exposing the specimens to predetermined solutions for the period of exposure. All through the experimental work, consistency in specimen preparation, curing, loading, and measurement methods were maintained.

3.5. Assessment of Compressive Strength

Cube specimens with curing ages of 7, 14, and 28 days were used to test compressive strength, as per the Bureau of Indian Standards' standards. The compressive strength is calculated by dividing the failure load applied to the specimens by the loaded surface area.

$$\text{Formula: fck} = \frac{P}{A} \quad (1)$$

Where:
Compressive Strength (in MPa) = fck
P is the applied load at failure (in N).

3.6. Test of Flexural Strength

The prism specimens underwent two-point loading for the flexural strength tests, as specified in the Bureau of Indian Standards.

$$\text{Formula: fr} = \frac{PL}{bd^2} \qquad (2)$$

Where: Fr (flexural strength), P (load), L (span length), b (width), and d (depth) are the variables.

3.7. Tests on Durability

The samples were immersed in different solutions of sodium silicate and hydrochloric acid for an additional period of 28 days after the curing period of 28 days. Thus, the age of the samples is fifty-six days.

The following was used to calculate the residual strength loss:

$$\text{Strength Loss (\%)} = \frac{f_{28} - f_{56}}{f_{28}} \text{x}100 \qquad (3)$$

Where f_{28} = 28-day compressive strength and f_{56} = residual strength after chemical exposure

3.8. Stress-Strain Analysis and Elastic Modulus

The stress-strain curve was determined by the cylinder equivalent compressive strength and the longitudinal compressometer. The stress peak occurred around a strain of 0.002, and the post-failure softening continued to a strain of 0.0035. Elastic modulus was determined from the linear elastic portion:

$$E = (\sigma2 - \sigma1)/(\varepsilon2 - \varepsilon1) \qquad (4)$$

Where E = elastic modulus (MPa) $\sigma1, \sigma2$ = stresses in elastic range and $\varepsilon1, \varepsilon2$ = corresponding strains

3.9. X-Ray Diffraction Analysis

To categorize the phases current in the hydrated concrete system, as well as to identify changes in the mineralogy due to blended cement replacement, X-ray diffraction examination was executed.

The formation of phases and the development of mechanical strength were correlated, as revealed from the results. The existence of major crystalline materials in the hydrated system was revealed by observing distinct diffraction peaks for quartz, calcite, portlandite, and dolomite.

3.10. Statistical Analysis

A statistical analysis was executed to enhance the accuracy of the experimental results that have been attained through testing various types of concrete mixtures. The results achieved for each of the engineering properties were analysed to obtain an average result that would be least affected by the variations that may have occurred in the process of conducting the experiment.

Statistical analysis was done to distinguish the difference in behaviour between the control and blended concrete mixtures and to detect the significant difference at different replacement levels.

3.11. Experimental Procedure

This research work utilized a stepwise experimental procedure involving material selection and characterization, mixture proportioning considering the replacement percentage of dolomite powder and sugarcane bagasse ash. Concrete mixes were made, cast in moulds, and subjected to laboratory curing prior to evaluation of mechanical and durability performances and microstructure examination.

Tests for mechanical properties consisted of compressive strength, flexural strength, stress-strain curve, and modulus of elasticity, while those for durability properties include exposure to chemicals and water absorption tests. Lastly, XRD analysis was done to do the nature of hydration products and correlate microstructure with engineering performance.

4. Results

The experimental program provided various concrete properties, such as mechanical properties, durability properties, stress-strain properties, elastic modulus properties, and microstructural properties, for five different concrete mixes designed to gradually replace cement by weight with dolomite powder and sugarcane bagasse ash.

The experiment's findings show that the exposure environment, curing period, and degree of material substitution all have a major impact on concrete's performance. All the mixes created in the experiment had better quality at the moderate replacement level, while the high replacement level often showed lower values because of dilution effects on the binder and hydration reaction efficiency.

4.1. Results of Compression Strength

With the experimentation of the compressive strength test, it is evident that there is an raise in strength of all the concrete cube with respect to age of 7, 14, and 28 days, where M3 was found to have the best strength among all the mixes.

Figure 3 depicts the setup for testing compressive strength and the cubes formed using the concrete mixes. The first figure represents the compression machine, which applies axial force on hardened concrete samples.

The second figure shows the marked cubes representing each mix combination tested at curing periods. The cubes were utilized to study the effect of dolomite powder and sugarcane bagasse ash on the compressive strength property.

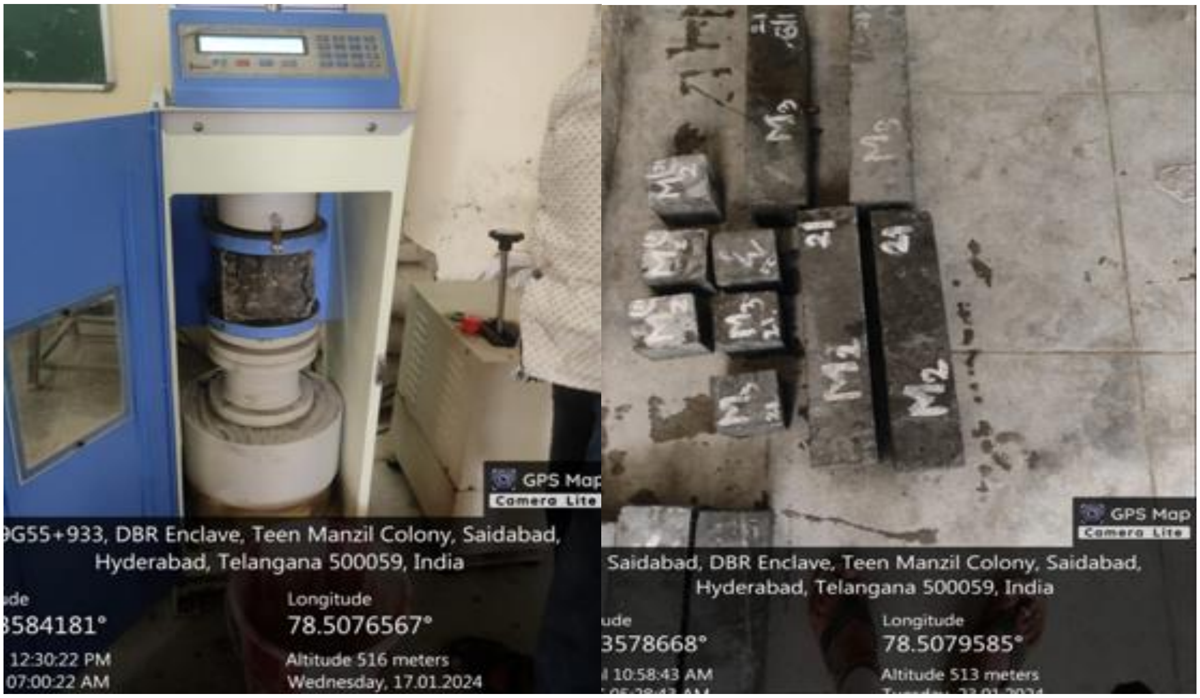

Fig. 3 Compressive strength testing setup and cast concrete specimens used for mechanical evaluation

Table 8. Compressive strength results of blended concrete mixes at different curing ages

S. No.	Mix ID	7 Day Compressive Strength (MPa)	14 Day Compressive Strength (MPa)	28 Day Compressive Strength (MPa)
1	M1	28.95	36.84	41.76
2	M2	28.54	36.21	41.23
3	M3	33.48	42.11	47.84
4	M4	23.64	30.86	34.77
5	M5	22.91	29.98	33.84

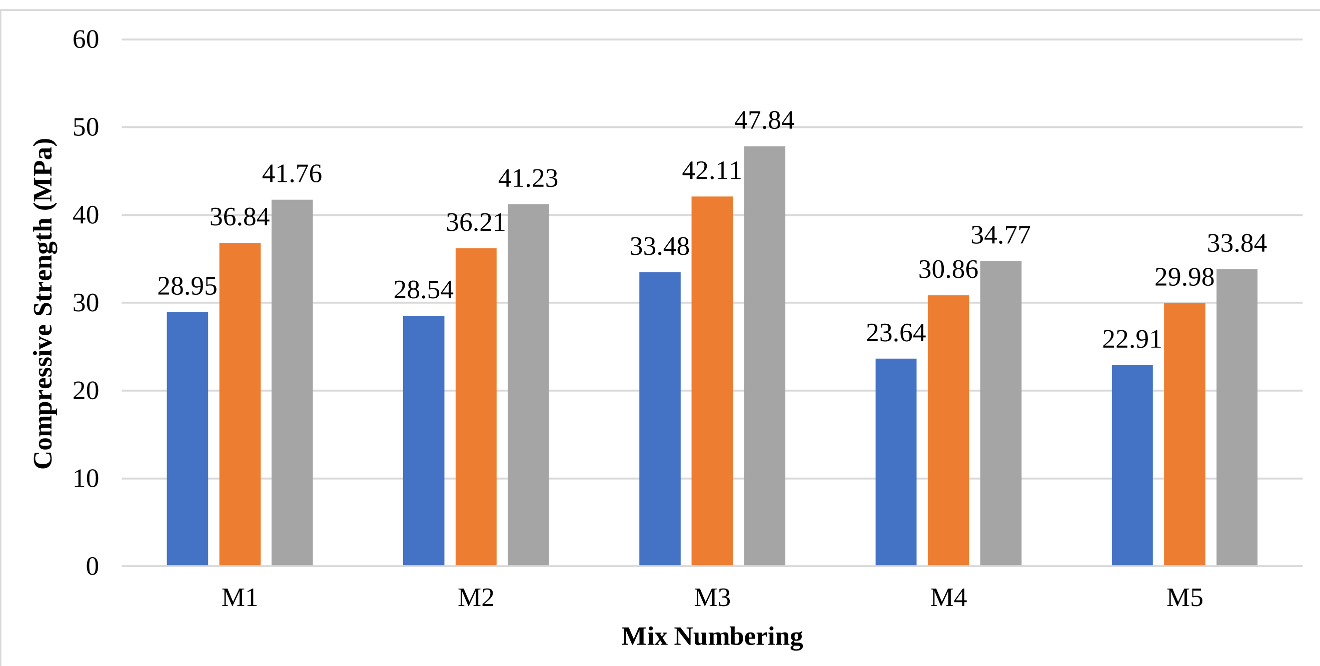

Fig. 4 Compressive strength variation of blended concrete compositions after 7, 14, and 28 day

The compressive strength development of concrete blends is presented in Table 8 and Figure 4, where values are provided for 7, 14, and 28 days of curing. For all the test cubes, compressive strength increased continuously as curing time increased, suggesting good hydration behaviour. The best performing mix in all cases was M3, which attained the highest strength value of 47.84 MPa at 28 days due to the optimal inclusion of dolomite powder and sugarcane bagasse ash.

4.1.1. Statistical Analysis of Compressive Strength

The obtained data on compression strength shows a clear trend of development of strength properties with increasing curing time for all examined mixtures, showing the efficiency of the hydration process. Among all tested mixtures, M3 proved to have the highest compressive strength values, which means that chosen binary replacement ratio contributed to obtaining the best ratio between hydration process, fillers activity, and pozzolanic activity. The lower replacement ratio resulted in minor gains, while the high ratio decreased strength because of the dilution of the clinker. Variation in the obtained results between different concrete mixtures proved to be systematic, which shows good experimental results and confirms the impact of the replacement ratios on the concrete mixtures' properties.

4.2. Results of Flexural Strength

Table 9. Flexural Strength Test Results

S. No.	Mix ID	7 Day Flexural Strength (MPa)	14 Day Flexural Strength (MPa)	28 Day Flexural Strength (MPa)
1	M1	3.18	4.02	4.52
2	M2	3.14	3.98	4.48
3	M3	3.39	4.33	4.84
4	M4	2.89	3.68	4.12
5	M5	2.84	3.61	4.05

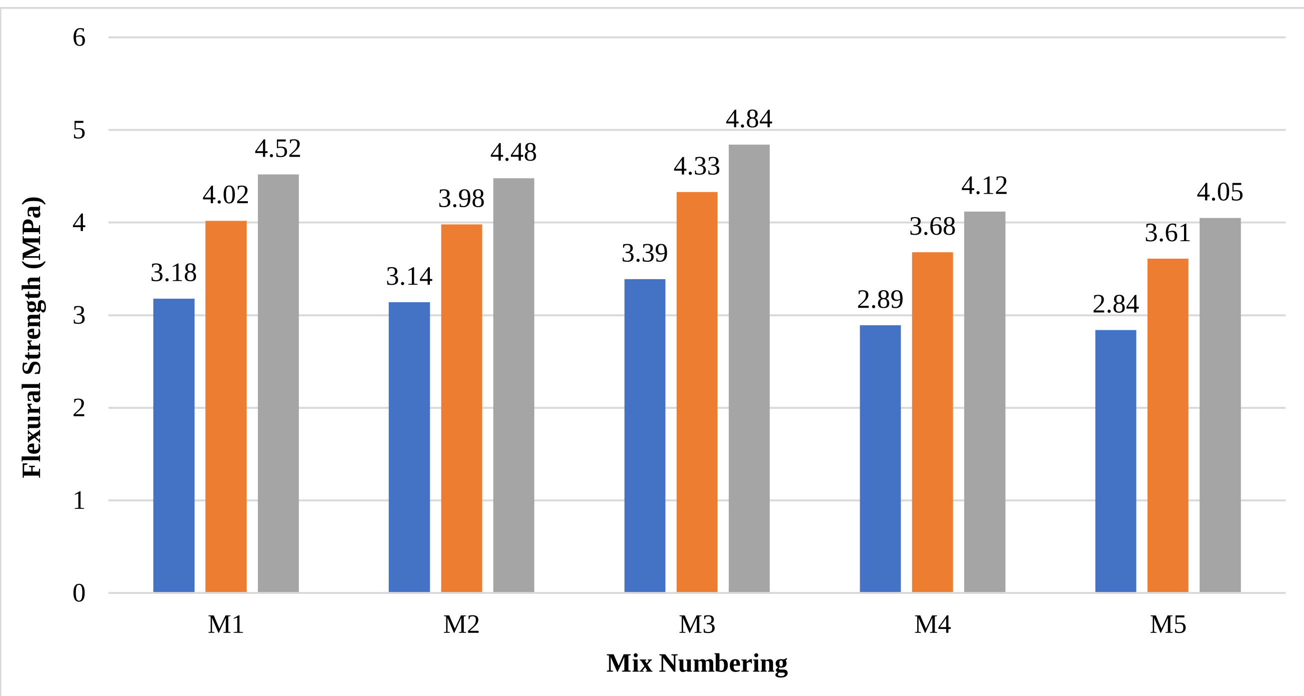

Fig. 5 Age-wise flexural strength variation of concrete containing dolomite powder and sugarcane bagasse ash

Table 9 and Figure 5 presents the flexural strength performance of blended concrete mixes measured at 7, 14, and 28 days of curing. All mixes showed gradual strength improvement with curing age due to continued hydration and matrix densification. Mix M3 exhibited the highest flexural strength of 4.84 MPa at 28 days, indicating improved crack resistance and tensile behavior under bending. Lower values observed in M4 and M5 suggest that excessive replacement levels reduce effective bonding within the concrete matrix.

4.2.1. Engineering Interpretation of Flexural Strength Test

According to the test results on flexural strength, the incorporation of dolomite powder and sugarcane bagasse ash in binary form has had a positive effect on the tensile properties of concrete at moderate levels of replacement. The increase in the flexural strength of M3 mix could be due to better interfacial bonding, denser porosity structure, and greater production of hydration products, which helped retard the cracking process in bending loads. On the contrary, high levels of replacements decreased the quantity of cementitious materials in the mixes, thus reducing the tensile resistance.

4.3. Durability Results under Sodium nitrate Exposure

Table 10 shows the resistance of blends of concrete mixes subjected to sodium nitrate solution based on comparison of 28-day compressive strength and 56 days post exposure compressive strength.

All mixes have shown a decrease in compressive strength due to chemical reaction. The mix having minimum loss is mix M3, which has shown loss of only 3.6% and hence indicates better resistance. On the other hand, mixes of M4 & M5 have shown comparatively higher strength losses.

4.3.1. Engineering Explanation of Chemical Durability

The durability test results show that the addition of optimal percentages of dolomite powder and sugarcane bagasse ash increased the ability of the concrete to withstand adverse conditions of the aggressive chemicals environment. This improved durability was mainly caused by the optimization of the porosity and decrease in the interconnected capillary voids, which prevented the diffusion of the aggressive ions inside the cement paste. The optimum binary blend retained better residual strength under chemical attacks, which means better microstructure stability. However, the high-replacement percentages showed more deterioration due to less hydration reaction and poor matrix cohesion.

Table 10. Acid resistance performance of blended concrete mixtures under Sodium nitrate exposure

S. No.	Mix ID	Description	28-Day Compressive Strength (MPa)	56-Day Strength after Sodium nitrate Exposure (MPa)	Strength Loss (%)
1	M1	Control mix	41.76	39.95	4.33
2	M2	5% DP + 2.5% SCBA	41.23	39.32	4.63
3	M3	10% DP + 5% SCBA	47.84	46.12	3.6
4	M4	15% DP + 7.5% SCBA	34.77	32.91	5.35
5	M5	20% DP + 10% SCBA	33.84	31.85	5.88

4.4. Durability Results under Magnesium sulfate Exposure

The durability characteristics of specimens made from blended concrete exposed for long periods to magnesium sulfate solutions have been presented in Table 11. Compressive strength was seen to decrease in all mixes because of sulfates on hydrated compounds and pores in the matrix. Mix M3 maintained its maximum strength, with the least loss of 6.31%. On the other hand, mixes of M4 and M5 experienced higher deterioration due to their high replacement ratios.

Table 11. Durability performance of blended concrete mixes under Magnesium sulfate exposure

S. No.	Mix ID	Description	28-Day Compressive Strength (MPa)	56-Day Strength after Magnesium sulfate Exposure (MPa)	Strength Loss (%)
1	M1	Control mix	41.76	38.72	7.28
2	M2	5% DP + 2.5% SCBA	41.23	38.05	7.71
3	M3	10% DP + 5% SCBA	47.84	44.82	6.31
4	M4	15% DP + 7.5% SCBA	34.77	31.36	9.81
5	M5	20% DP + 10% SCBA	33.84	30.18	10.82

4.5. Durability Results under Sulfuric acid Exposure

Table 12 illustrates the behavior of blended concrete mixtures under sulfuric acid attack through the assessment of strength losses after chemical attack. It is evident from the analysis that acidic attacks led to considerable damage to the concrete mixture because of the breakdown of the hydrated compounds in cement. In particular, the M3 mix suffered the least loss of strength of 10.2%, thus indicating superior performance in resisting acid attacks due to optimum replacement ratios.

Table 12. Durability performance of blended concrete mixes under Sulfuric acid Exposure

S. No.	Mix ID	Description	28-Day Compressive Strength (MPa)	56-Day Strength after Sulfuric acid Exposure (MPa)	Strength Loss (%)
1	M1	Control mix	41.76	36.82	11.83
2	M2	5% DP + 2.5% SCBA	41.23	36.02	12.64
3	M3	10% DP + 5% SCBA	47.84	42.96	10.20
4	M4	15% DP + 7.5% SCBA	34.77	29.58	14.93
5	M5	20% DP + 10% SCBA	33.84	28.11	16.93

4.6. Durability Results under Sodium Chloride

Table 13. Durability performance of blended concrete mixes under Sodium chloride exposure

S. No.	Mix ID	Description	28-Day Compressive Strength (MPa)	56-Day Strength after Sodium chloride Exposure (MPa)	Strength Loss (%)
1	M1	Control mix	41.76	40.11	3.95
2	M2	5% DP + 2.5% SCBA	41.23	39.41	4.41
3	M3	10% DP + 5% SCBA	47.84	46.05	3.74
4	M4	15% DP + 7.5% SCBA	34.77	33.07	4.89
5	M5	20% DP + 10% SCBA	33.84	31.98	5.5

Table 13 displays the response of durable behavior in the combined concrete mixtures due to their exposure to sodium chloride through the ratio between their original strength and residual strength. The strength of the specimens was slightly lowered because the chloride ions were absorbed in the concrete structure, affecting their stability. Specimen M3 exhibited the lowest strength deterioration with 3.74%, signifying its greater resistance to the absorption of the chloride ions.

4.7. Durability Results under Water Absorption

Water absorption properties for the blended concrete mixtures were assessed using Table 14 based on dry and wet weights. Lesser values denote lower pore interconnectivity and better compactness of the concrete. Concrete mixture M3 had the lowest water absorption value of 3.52%, which is indicative of refined pores in this mixture owing to equal proportions of dolomite powder and sugarcane bagasse ash used in its blend.

4.7.1. Engineering Explanation of Water Absorption

Clearly, there is an effect of binary supplementary cementitious material on the internal porosity of the concrete from the water absorption analysis. The minimum water absorption achieved by the concrete mixture M3 implies that there was formation of a denser and more uniform cementitious matrix due to better particle packing and second hydration reactions. The reduced pore connection reduces moisture penetration and increases the resistance to deterioration. Excessively high amounts of replacement led to increased water absorption due to an insufficient number of cementitious materials needed to fill internal voids. Thus, the ideal binary replacement ratio improved matrix density.

Table 14. Durability performance of blended concrete mixes under Water Absorption

S. No.	Mix ID	Description	Dry Weight (kg)	Wet Weight (kg)	Water Absorption (%)
1	M1	Control mix	8.2	8.52	3.9
2	M2	5% DP + 2.5% SCBA	8.18	8.51	4.03
3	M3	10% DP + 5% SCBA	8.25	8.54	3.52
4	M4	15% DP + 7.5% SCBA	8.14	8.53	4.79
5	M5	20% DP + 10% SCBA	8.1	8.51	5.06

4.8. Stress-Strain and Elastic Modulus Results

Table 15 and Figure 6 highlights the stress-strain characteristics of the hybrid concrete specimens derived from compressometer readings along the axial direction. An increase in the level of stress with strain was observed until the stress attained maximum value, after which there was a decline, showing the stress-deformation characteristic beyond the peak point. The specimen M3 gave the highest level of stress value of 17.40 MPa for strain value of 0.002.

4.8.1. Engineering Understanding of Stress-Strain Behavior

The stress-strain properties show that the binary-blended concrete retained its usual nonlinear performance for cementitious materials with an improved load-bearing capacity due to optimal substitution of the material.

The increased peak stress and higher elastic modulus for the M3 mixture imply increased stiffness and improved deformation resistance due to compression of the material. This is related to the improved interactions between aggregate and paste because of the fillers and pozzolan in the blend. In contrast, too much substitution decreased the stiffness of the material due to weak cementitious bonding.

Table 15. Stress–strain response of concrete mixes obtained from longitudinal compressometer analysis

Strain	Stress for M1	Stress for M2	Stress for M3	Stress for M4	Stress for M5
0.0005	8.35	8.24	8.70	6.96	6.77
0.0010	16.70	16.49	17.40	13.91	13.54
0.0015	25.06	24.73	26.10	20.87	20.30
0.0020	33.41	32.98	38.27	27.82	27.07
0.0025	30.74	30.34	35.21	25.59	24.90
0.0030	27.40	27.04	31.38	22.81	22.20
0.0035	23.39	23.09	26.80	19.47	18.94

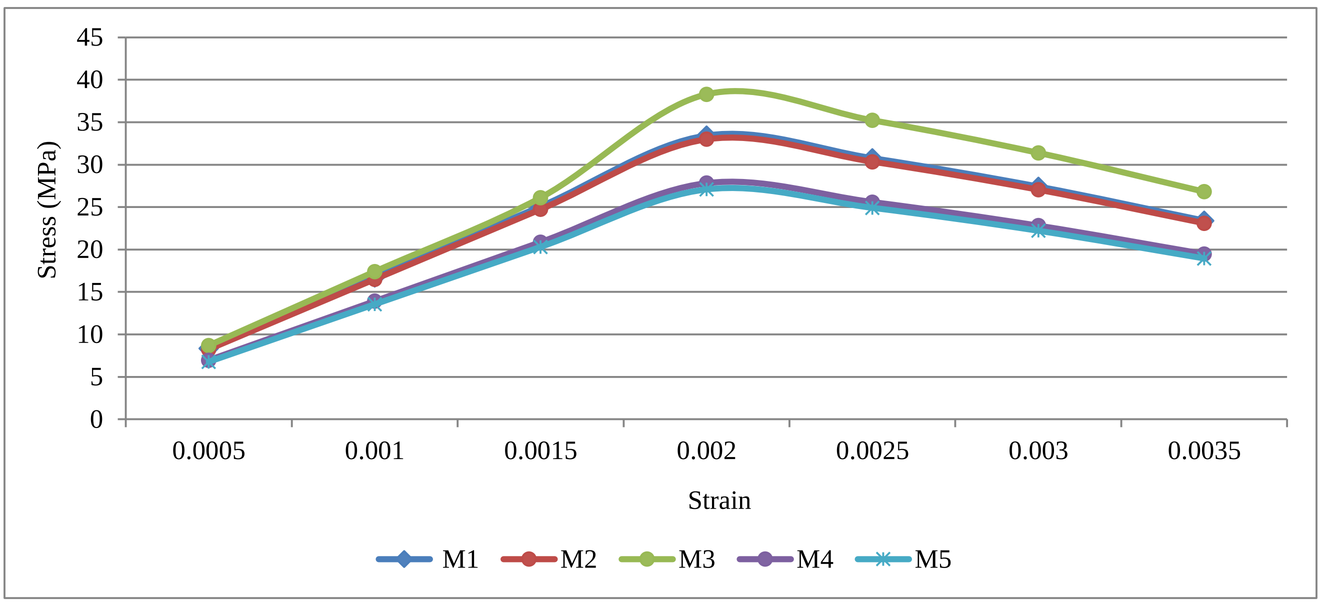

Fig. 6 Comparative stress–strain curves of M1 to M5 concrete mixes

Table 16 shows the elastic modulus determined by stress-strain tests on all concrete mixtures, evaluated by calculating the slope of the linear elastic portion of the stress-strain curve between two chosen stress-strain levels (σ1, σ2, ε1, ε2). The elastic modulus is evaluated by:

$$E = (\sigma 2 - \sigma 1)/(\varepsilon 2 - \varepsilon 1)$$

M1 control mix displayed a stiffness of 16700 MPa. It was clear that this mix provided an ordinary stiffness response in terms of the properties of M30 concrete. On the other hand, M2 displayed an insignificant decrease in stiffness to 16500 MPa.

Mix M3, however, provided the highest stiffness response of 17400 MPa, implying an optimal stiffness improvement resulting from an optimal combination of both DP and SCBA that led to more rigid structure and better load transfer capacity. On the contrary, the stiffnesses for M4 and M5 were significantly lower (13900 MPa and 13540 MPa).

Table 16. Elastic Modulus Results

S. No.	Mix ID	σ_1 (MPa)	σ_2 (MPa)	ε_1	ε_2	Elastic Modulus (MPa)
1	M1	8.35	16.7	0.0005	0.001	16700
2	M2	8.24	16.49	0.0005	0.001	16500
3	M3	8.7	17.4	0.0005	0.001	17400
4	M4	6.96	13.91	0.0005	0.001	13900
5	M5	6.77	13.54	0.0005	0.001	13540

4.9. XRD Results

The XRD results identified quartz, calcite, portlandite, and dolomite as primary crystalline phases. The modified mixes had lower portlandite peak intensities compared with normal concrete, indicating pozzolanic reaction with calcium hydroxide. M3 had the strongest amorphous background, verifying improved calcium silicate hydrate production. At higher replacement levels, hydration peaks were reduced due to clinker dilution effects.

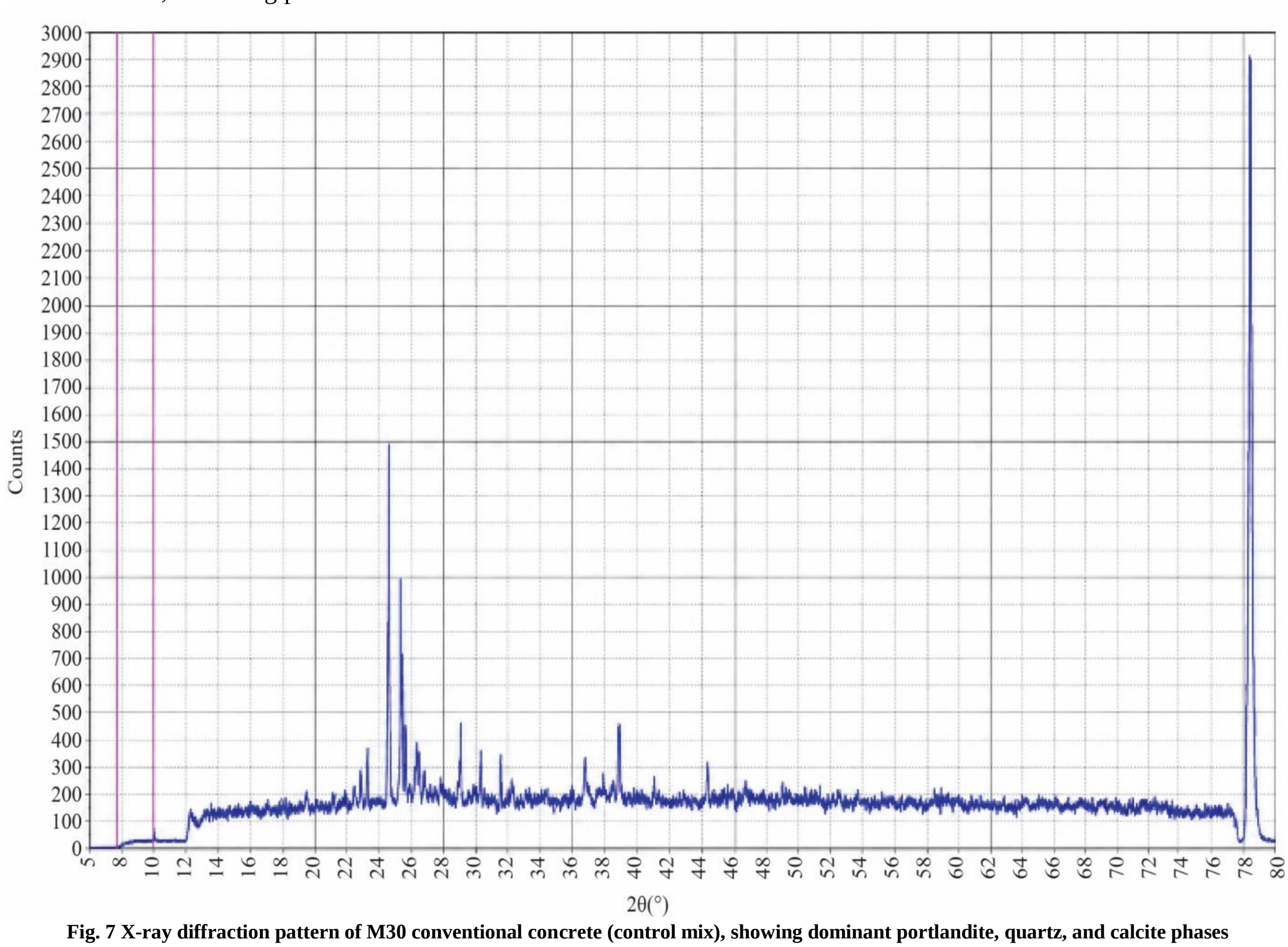

Fig. 7 X-ray diffraction pattern of M30 conventional concrete (control mix), showing dominant portlandite, quartz, and calcite phases

The X-ray diffraction results of the control concrete specimen are shown in Figure 7, which shows the crystal phases produced from the hydration process. The significant peaks in this graph are those of portlandite, quartz, and calcite, which reflect the regular hydration of cement and the aggregates. Portlandite is evidence of the creation of calcium hydroxide, quartz indicates the siliceous nature of the aggregates, while calcite indicates the presence of carbonates in the mixture.

X-ray diffraction results from mix M2 are presented in Figure 8 below; there is an observed decrease in the intensity of the portlandite peak for the mixture.

It can be seen from the graph that there has been a commencement of pozzolanic action between the by-products of the hydration process and the sugarcane bagasse ash. Secondary product formations play a role in helping densify the matrix structure.

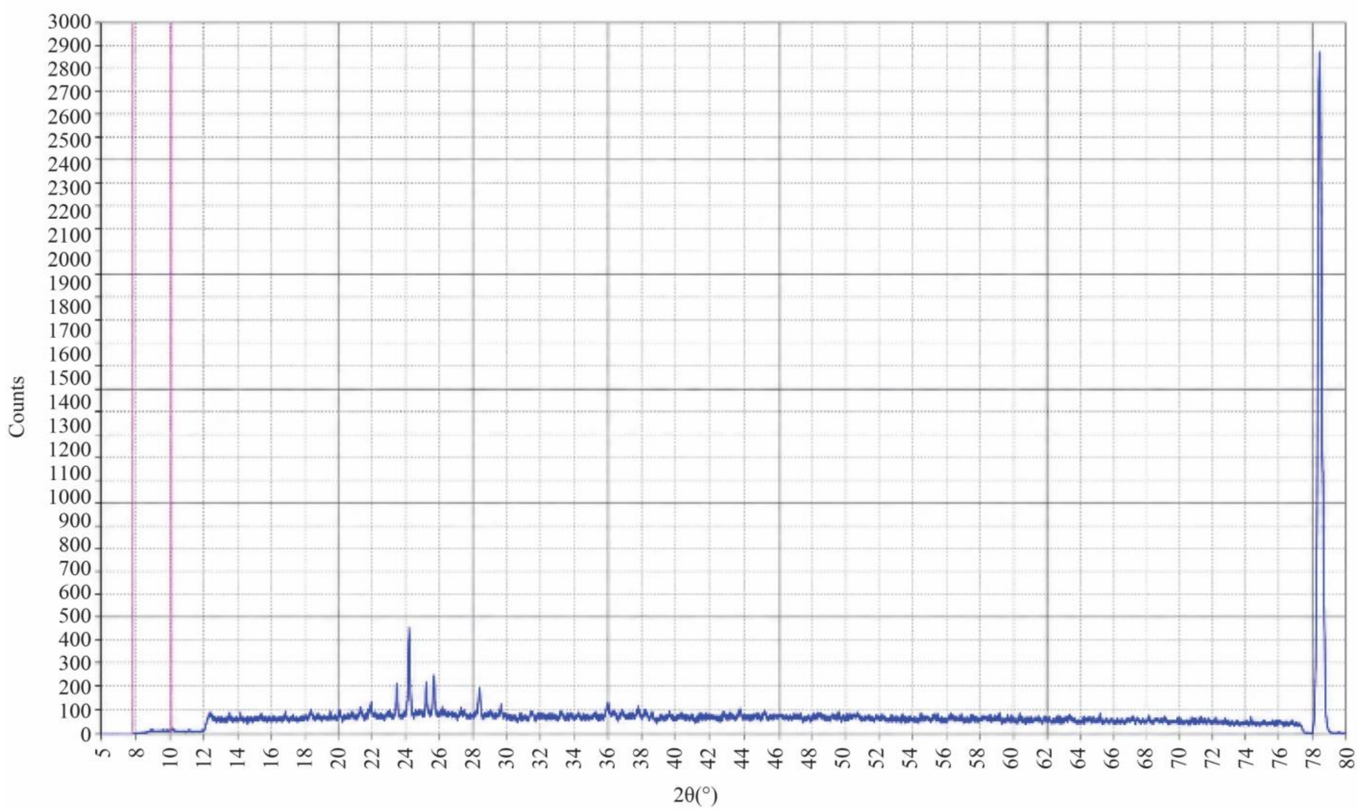

Fig. 8 XRD pattern of M2 illustrating reduced portlandite intensity and initiation of pozzolanic reactions

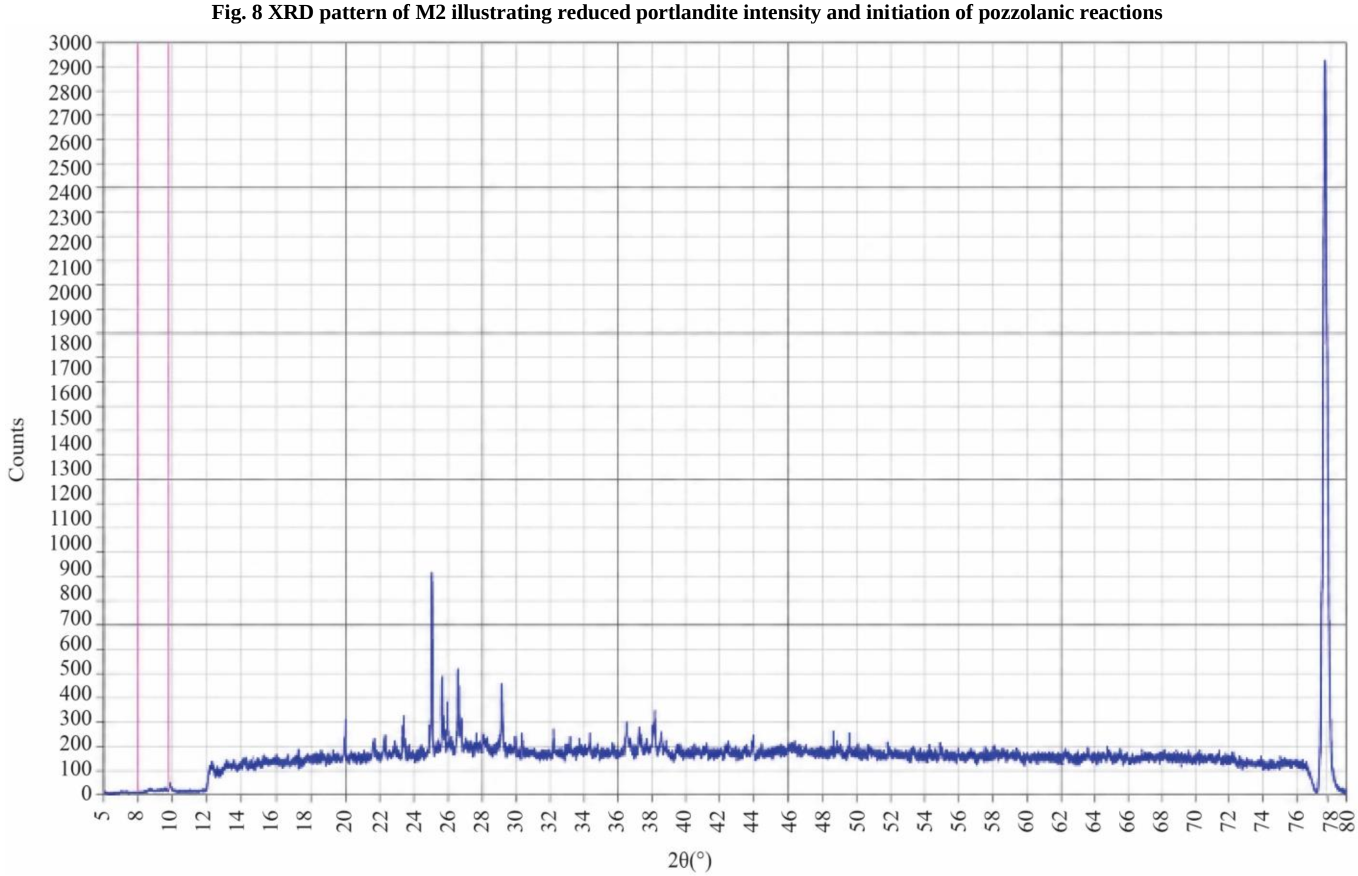

Fig. 9 XRD pattern of M3 showing enhanced amorphous C–S–H formation due to effective dolomite–SCBA interaction

Figure 9 shows the XRD analysis of mixture M3, with a modified peak distribution suggesting more active pozzolanic and filler effects of dolomite powder on sugarcane bagasse ash. In addition to the lower presence of portlandite, the broadened background spectrum supports increased amorphous calcium-silicate-hydrate gel generation. Such a dense hydration system accounts for the better mechanical and durability properties of M3, indicating that the chosen substitution ratio achieved the best internal microstructure formation.

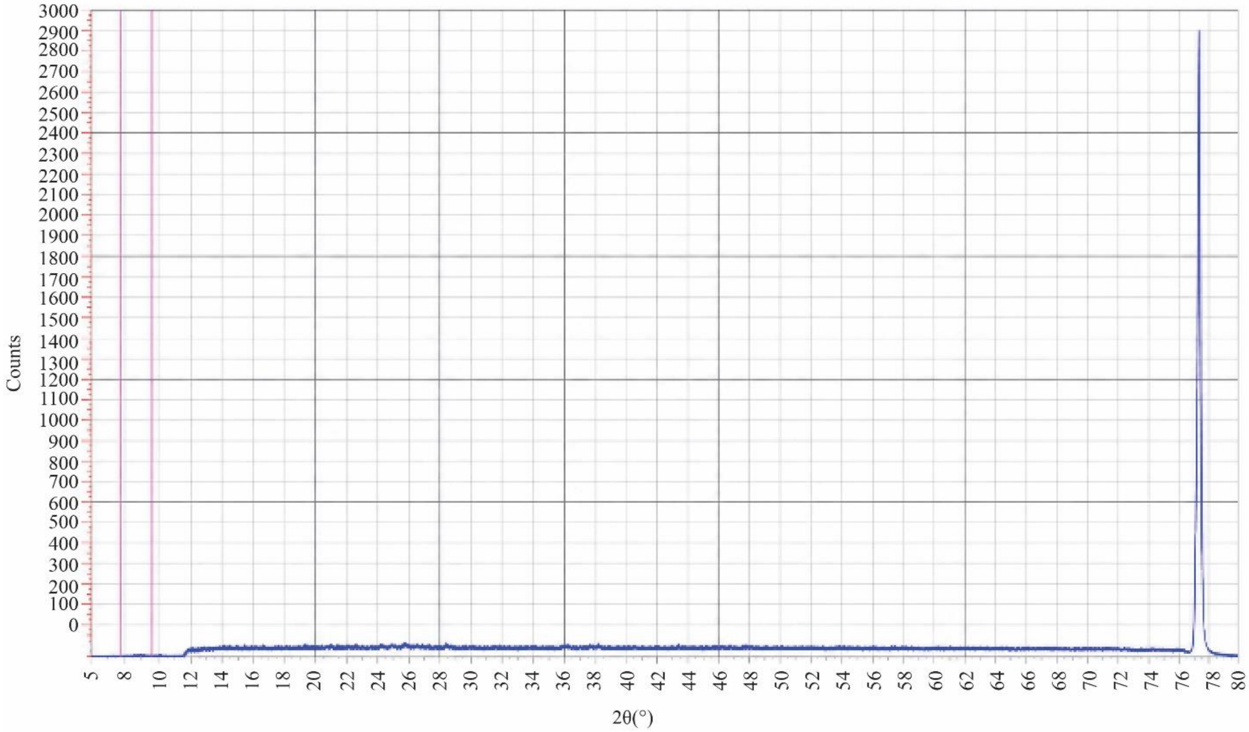

Fig. 10 XRD pattern of M4 indicating maximum portlandite consumption and densified hydration products

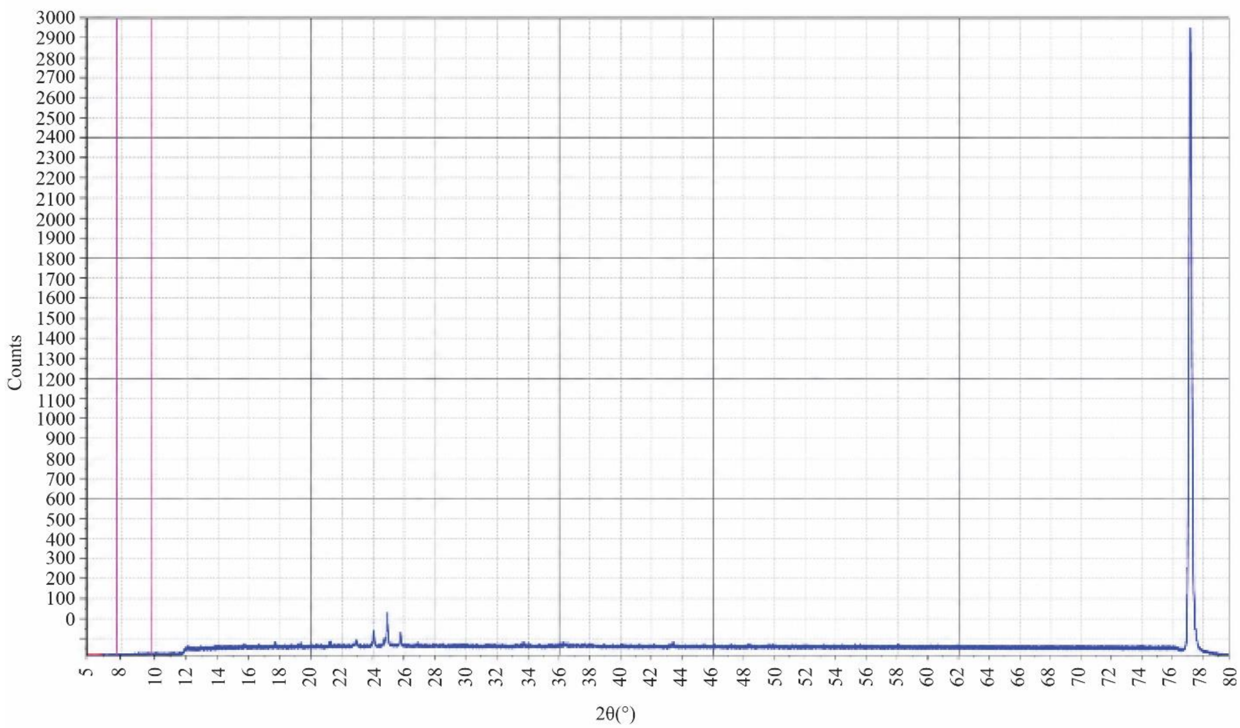

Fig. 11 XRD pattern of M5 highlighting dilution effects at higher cement replacement levels

XRD patterns for sample M4 are illustrated in Figure 10, and here there is another reduction in the peaks corresponding to portlandite, showing a great use of calcium hydroxide in the reactions that occurred. This pattern implies a higher density of the hydration products formed, along with higher amorphousness in the mixture. Nevertheless, while there was a significant increase in the chemical reactivity of the mixture, the substitution was too much, resulting in decreased strength of the mixture.

Figure 11 gives the XRD analysis result of mix M5, where the low intensity of peaks indicates the high amount of dilution in cement hydration products in mixtures with high replacements. The minimal amount of portlandite formation and its poor crystal structure formation show that an excess of dolomite powder and sugarcane bagasse ash reduced the reactivity of the cement components. This decreased reactivity led to poor matrix formation.

4.9.1. Engineering Explanation of XRD Results

The XRD results have clearly confirmed the changes made in the microstructure due to the replacement of the binary cement. The decrease in the intensity of portlandite peak, along with the increase in the amorphous hydration phase, has clearly indicated that there has been an improvement in the pozzolanic activity and generation of further calcium silicate hydrate minerals. The changes in the minerals have helped to explain the improvements in the mechanical and durability performance of the optimal concrete mix. It is because the dense hydration products helped in improving the continuity of the matrix and pore connectivity, while high replacement led to low hydration intensity due to dilution of the cement.

5. Discussion

The interpretation of experimental results for the mechanical, durability, deformation, and microstructure testing of blends of concrete containing dolomite powder and sugarcane bagasse ash is given in Section 5. The interpretation establishes the relationship between strength formation, hydration, pore structure modification, and chemical resistance when subjected to an aggressive environment. Of particular concern is determining the best replacement ratio using a comparative assessment of compressive and flexural strengths, modulus of elasticity, water absorption, and X-ray diffraction studies.

5.1. Effect of Binary Cement Replacement with Dolomite Powder and Sugarcane Bagasse Ash on Mechanical Strength Properties

The results from mechanical strength properties have shown a clear relationship between mechanical strengths and the use of binary cement replacements with dolomite powder and sugarcane bagasse ash. The increase in the compressive and flexural strengths can be observed in mixes M1 to M3, which had compressive strengths of 47.84 MPa and flexural strengths of 4.84 MPa. These values were obtained when the mix contained 10% dolomite powder and 5% SCBA. Improvement in strength development was due to the filler effect of dolomite powder and silica reaction with SCBA, forming more calcium-silicate-hydrate gels.

5.2. Behavior of Stress and Strain and Elastic Modulus Properties

Analysis of stress and strain depicted conventional stress-strain characteristics of concrete with stiffness dependent on substitution rate. The highest value of maximum stress was obtained for the M3 specimen of 38.27 MPa at 0.002 strain value, suggesting increased load-bearing capacity and enhanced structural stability of concrete. The slope of the stress-strain curve at the initial stage was found to be higher than that of other mixes, thus reflecting greater stiffness. Calculations of elastic modules demonstrated optimum properties of specimen M3, which had an elastic modulus of 17.40 MPa, exceeding the elastic modulus of the control specimen.

5.3. Chemical Durability Performance under Aggressively Exposed Conditions

Chemical durability testing was carried out using sodium nitrate, magnesium sulfate, sulfuric acid, and sodium chloride, and it was observed that there was an increase in the performance of the concrete mixes with the optimum replacement ratio. Mixture M3 performed well in resisting strength loss under various aggressive conditions, with the following percentage values; 3.6% with sodium nitrate, 6.31% with magnesium sulfate, 10.2% with sulfuric acid, and 3.74% with sodium chloride. Lower loss of strength in the mixture is indicative of better pore structures with lower permeability. The reason for increased strength loss was due to lower cement hydration.

5.4. Water Absorption and Porosity Refinement Process Mechanism

Water absorption effects directly indicate porosity refinements attained due to interactions by additional materials. The lowest water absorption rate, 3.52%, was obtained from mixture M3, thus signifying good density and less capillary connection. Dolomite fine powder served as a filler by filling gaps between the cement particles, and sugarcane bagasse ash provided silica that took part in the secondary hydration process. In this way, there was a reduction in pore connectivity, hence improved porosity refinement within. However, mixture M4 and M5 recorded higher absorption rates of 4.79% and 5.06%, respectively.

5.5. Mineralogy Identification Based on X-Ray Diffraction Study

The hydration phases of each mix have been characterized by using X-ray diffractometry. The control concrete revealed the dominance of portlandite, quartz, and calcite peaks, which are common hydrated products in the normal cement hydration process. The mixture M2 demonstrated a lower intensity of portlandite, showing that the pozzolanic reaction was activated in this case. In the mixture M3, a higher intensity of amorphous structure was noticed along with the lower intensity of calcium hydroxide, which proves an increase in calcium silicate hydrate due to successful reaction between dolomite and SCBA.

5.6. Mechanism for Optimum Performance of M3 Mix

The M3 mix always gave optimum performance because of the optimum replacement ratio of the fillers, which ensured that filler effect, pozzolanic effect, and hydration of cement were all maintained in an optimal manner. Dolomite powder ensured good packing of particles and a reduction in internal void space. The addition of sugarcane bagasse ash provided reactive silicon dioxide, which reacted with the calcium hydroxide and formed the secondary gel, Ca-Si-H. All of these factors resulted in increased strength and durability while reducing water uptake.

5.7. Comparison with Previous Literature

The results obtained are consistent with the previous studies demonstrating that partial incorporation of dolomite powder leads to enhanced packing density and early hydration, whereas sugarcane bagasse ash provides a pozzolanic reinforcement effect due to silica activity. In the related literature, it has been found that optimal partial replacement enhances the mechanical properties and durability solely when cement hydration is adequate. The excellent behavior of M3 can be attributed to the positive impacts of both filler and pozzolanic effects previously documented. On the other hand, the decrease in strength at higher replacement ratios is consistent with the previously reported negative consequences of cement dilution.

5.8. Engineering Significance of the Optimum Composition of M3 for Practical Application in Construction

It is worth mentioning that the optimum composition of M3 shows great prospects for practical use in the construction of structural concrete products in which durability and sustainability are of equal importance. The higher compressive and flexural strengths of this mixture make it appropriate for use in beams, slabs, pavements, and prefabricated structural members. Increased elastic modulus contributes to better serviceability since this leads to less deformation under loading. Increased resistance to sulfuric acid, chloride, nitrate, and acidic environments makes the M3 mixture especially suitable for use in maritime, chemical plant, sewage system, and agricultural building construction.

5.9. Scientific Novelty and Significance of the Current Research

The main scientific novelty of this research is the combination of mechanical properties, durability, deformability, and microstructure studies conducted on one binary blended concrete matrix that incorporates dolomite powder and sugarcane bagasse ash. While most prior research concentrate their efforts on the determination of compressive strength only, this paper includes bending performance, stress-strain curves, elastic modulus, various chemical attacks, water absorption, and XRD phase analyses. The definition of M3 as an optimal substitution ratio by several engineering criteria is highly valuable in practice.

5.10. Practical Engineering Applications of the Experiment Results

The results obtained through the experiment show that using the binary blends of the dolomite powder and the sugarcane bagasse ash is an effective way to create sustainable concrete structures without sacrificing their engineering properties. In fact, the optimal mix provided higher strength, better durability, and better microstructure, which made it appropriate to use in reinforced concrete structures, pavements, pre-stressed concrete structures, retaining walls, and in other infrastructure works.

The use of waste products also contributes to saving resources since it lowers the amount of cement used and promotes the use of waste materials. Thus, the developed binary blend of concrete may have a good application perspective in engineering practice.

Table 17. Comparative performance summary of control and optimum blended concrete mix

S. No.	Parameter	Control Mix (M1)	Optimum Mix (M3)	Performance Observation
1	28-Day Compressive Strength (MPa)	41.76	47.84	M3 showed significant strength improvement.
2	28-Day Flexural Strength (MPa)	4.52	4.84	Improved tensile bending resistance
3	Peak Stress (MPa)	33.41	38.27	Higher load carrying capacity in M3
4	Elastic Modulus (MPa)	16,700	17,400	Increased stiffness observed
5	Water Absorption (%)	3.9	3.52	Reduced pore connectivity in M3
6	Sodium Nitrate Strength Loss (%)	4.33	3.6	Better nitrate resistance
7	Magnesium Sulfate Strength Loss (%)	7.28	6.31	Improved sulphate durability

8	Sulfuric Acid Strength Loss (%)	11.83	10.2	Enhanced acid resistance
9	Sodium Chloride Strength Loss (%)	3.95	3.74	Lower chloride penetration effect
10	XRD Observation	Portlandite dominant	Increased amorphous C–S–H	Denser hydration products

The comparison between the control mix (M1) and optimum mix (M3) is depicted in Table 17, which shows that a great deal of improvement has been observed in terms of both mechanical behavior and durability because of partial substitution with DP and SCBA. The optimum mix (M3) has shown better results in almost all aspects in comparison to the control mix (M1). There is an increase in compressive strength at 28 days from 41.76 MPa for M1 to 47.84 MPa for M3, indicating better load-bearing capabilities.

As can be seen, stress-strain characteristics have revealed that the peak stress has increased from 33.41 MPa to 38.27 MPa, whereas the elastic modulus has risen from 33,400 MPa to 34,800 MPa, suggesting better stiffness and enhanced elasticity resistance properties. Thus, M3 demonstrates better internal bonding and dense matrix formation. With respect to durability testing, the results have shown that water absorption has decreased from 3.9% to 3.52%, indicating that pores are less interconnected, hence resulting in better impermeability. Also, improved chemical resistance of M3 is noticeable because strength loss in aggressive medium exposure has been observed as follows: sodium nitrate from 4.33% to 3.6%; magnesium sulfate from 7.28% to 6.31%; sulfuric acid from 11.83% to 10.2%; and sodium chloride from 3.95% to 3.74%. XRD testing of microstructure validated these observations, whereby sample M1 had prominent peaks of portlandite, while M3 possessed higher formation of amorphous C-S-H. This denotes that there is greater secondary hydration in M3, and therefore denser hydration products. Therefore, M3 can be classified as the ideal mixture.

5.11. Limitations of Current Research

The current research has successfully identified the benefits of binary dolomite powder and sugarcane bagasse ash to enhance the engineering properties of M30 concrete, there are several limitations that need to be considered. The experiment was carried out under controlled laboratory conditions and involved only one grade of concrete and a relatively shorter curing time. No analysis regarding long-term durability concerning carbonation, freeze-thaw cycles, chloride ingress, and repeated loads have been undertaken. Moreover, field testing, life cycle assessment, economic feasibility, and large-scale production considerations have not been addressed within the current research scope.

5.12. Future Research Directions

Future study should examine the utilization of the dolomite powder-SCBA binary system in high-performance concrete, self-compacting concrete, and fiber-reinforced cementitious composites. Long-term durability will be assessed using chloride diffusion, carbonation resistance, sulfate resistance, freeze-thaw action, and marine environment tests must be done. In future investigations, it is also possible that there will be use of advanced microstructure analysis methods, computational modeling, and AI prediction models. Life cycle assessment, carbon footprint assessment, and economic assessment are also necessary in establishing the sustainability of such systems.

5.13. Sustainability Perspective

The use of dolomite powder and sugarcane bagasse ash as partial replacement for ordinary Portland cement enhances sustainability through decreasing dependency on the latter, thus making use of the available waste products from industry and agriculture. The experimental findings show that binary replacement under certain conditions can enhance the performance characteristics of the blend, while simultaneously contributing to resource conservation and waste utilization. Nonetheless, it is worth noting that the environmental impacts analyzed within the scope of this paper have been achieved due to decreased cement consumption and not through any form of life cycle analysis. Thus, further studies should be conducted regarding the carbon emissions and embodied energy of the system.

5.14. Practical Recommendations for Engineers

From the results obtained from the experiments conducted, the optimum replacement ratio found from the study can be considered for engineering applications where there is a need for better mechanical properties and better durability for the concrete used. The concrete can be used in houses, commercial buildings, roads, pre-cast products, retaining walls, and generally reinforced concrete constructions where the use of sustainable materials is recommended. Quality control is very important at material production and curing stages to get the best out of the concrete.

6. Conclusion

The current study showed that simultaneous use of dolomite powder and sugarcane bagasse ash in M30 grade concrete leads to a marked improvement in the mechanical behavior, durability, and microstructure of concrete. Out of all tested mixes, the M3 mix design using 10% dolomite powder and 5% sugarcane bagasse ash was found to yield the best result by giving a 28-day compressive strength of 47.84 MPa and a flexural strength of 4.84 MPa compared to the control concrete mix. Furthermore, the same mix showed a greater elastic modulus of 17400 MPa, showing high stiffness and load-carrying capacity under compression loading. Upon examining the effect of acidity on the durability of the mixes, it was found that the M3 mix suffered the least reduction in strength after exposure to acid attack, while having the least water absorption of 3.52%. Based on X-ray diffraction data, there was an enhanced formation of stable calcite-silicate phases, while the presence of unstable hydration products was minimal in the optimum binary system. Replacement above the optimal level adversely affected performance due to binder dilution and lack of hydration contribution. In conclusion, the systematic use of dolomite powder and sugarcane bagasse ash can provide a feasible and sustainable means of producing durable concrete structures.

Conflict of Interest

The authors state that there is no conflict of interest associated with this study.

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Author Contributions

Dhanamma Palsam: Conceptualization, Methodology, Experimental Investigation, Data Analysis, and Original Draft Preparation. Contribution by Murugan R. and Manohar G. includes conceptualization of the experiment, technical guidance, interpretation of the experimental data, and critical revision of the manuscript. They were also involved in the validation of results, intellectual editing of the manuscript, and approval of the manuscript for submission. All authors have read, revised, and approved the manuscript submitted for publication.

Ethics Approval

There were no human or animal experiments in this study. Thus, ethical approval was not necessary. The research followed institutional rules for academic research.

Data Availability

The experimental datasets supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

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