

Sustainable Concrete Using Alccofine, Fly Ash, and Dolomite Powder as Partial Cement Replacements

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Abstract: Ordinary Portland Cement (OPC) manufacturing is a major contributor to global carbon dioxide emissions and depletes finite limestone reserves, motivating the search for sustainable partial cement replacements. This study presents an experimental and microstructural investigation of concrete incorporating a ternary blend of supplementary cementitious materials (SCMs)- fly ash, Alccofine 1203, and dolomite powder- as partial replacements for cement. Concrete mixes of grades M30, M40, and M50 were proportioned to their respective target mean strengths, and specimens were cast and cured in water at 27 ± 2 °C. Compressive strength (150 mm cubes), flexural strength (100 × 100 × 500 mm beams under third-point loading), and split tensile strength (150 × 300 mm cylinders) were evaluated at 7, 28, 56, and 90 days in accordance with IS 516, IS 5816, ASTM C39, ASTM C78, and ASTM C496. Results show a consistent increase in all three strength parameters with curing age and with increasing target grade, with compressive strength gaining 18–20% beyond the 28-day value by 90 days, while flexural and split tensile strength gains over the same period were comparatively modest (7–16%). Split tensile strength remained the lowest of the three properties throughout, typically 6–8% of the compressive strength at 28 days, and the flexural-to-compressive and tensile-to-compressive ratios both decreased as grade increased. Scanning Electron Microscopy (SEM) of the hydrated matrix revealed a visible reduction in calcium hydroxide (portlandite) crystals and the formation of a denser calcium silicate hydrate (C-S-H) gel network in the ternary-blended mixes, consistent with pozzolanic consumption of portlandite and pore refinement. The findings confirm that a synergistic fly ash–Alccofine–dolomite blend can deliver strength development and microstructural densification comparable to, or exceeding, conventional OPC concrete while substituting a portion of cement, supporting its use as a sustainable alternative binder system for structural concrete.

Keywords: Sustainable concrete; Supplementary cementitious materials; Fly ash; Alccofine; Dolomite powder; Compressive strength; Flexural strength; Split tensile strength; Microstructure; SEM analysis

1. Introduction

The construction industry is the largest single consumer of natural resources in the world, and concrete, owing to its versatility, durability, and cost-effectiveness, remains the most widely used construction material. However, the production of Ordinary Portland Cement (OPC), the primary binder in concrete, is highly energy-intensive and is responsible for approximately 8% of global anthropogenic carbon dioxide emissions. Manufacturing one ton of cement releases roughly 0.9 tons of CO₂ into the atmosphere, largely through the calcination of limestone and the combustion of fuel required to reach clinkering temperatures. In parallel, the continued extraction of natural limestone reserves for cement production raises serious concerns regarding the long-term availability of this non-renewable resource. These environmental and resource-related pressures have driven a global shift toward sustainable concrete technologies that reduce dependence on OPC without compromising structural performance.

One of the most effective and widely adopted strategies for improving the sustainability of concrete is the partial replacement of cement with supplementary cementitious materials (SCMs). SCMs are typically industrial by-products or naturally occurring minerals that either react pozzolanically with the calcium hydroxide liberated during cement hydration, or act as inert or semi-reactive fillers that refine the pore structure of the hardened matrix. Common SCMs include fly ash, ground granulated blast furnace slag, silica fume, metakaolin, and, more recently, ultrafine reactive

powders such as Alccofine. Increasingly, research has also explored the use of finely ground limestone and dolomite powders as micro-fillers that improve particle packing and can chemically interact with aluminate phases in cement.

The present study investigates a ternary-blend approach that combines three materials with distinct and complementary roles: fly ash, a fine pozzolanic industrial by-product of coal combustion; Alccofine 1203, an ultrafine, highly reactive ground granulated slag-based SCM; and dolomite powder, a naturally occurring carbonate mineral used primarily as a micro-filler. The underlying hypothesis is that the combined use of these three materials can achieve synergy in strength development, workability, and cost-efficiency that individual SCMs used alone cannot fully deliver. This paper reports the mechanical performance- compressive, flexural, and split tensile strength- of M30, M40, and M50 grade concretes incorporating this ternary blend, evaluated across four curing ages (7, 28, 56, and 90 days), and complements these mechanical results with a microstructural investigation using Scanning Electron Microscopy (SEM) to relate observed strength trends to the underlying hydration and pore-refinement mechanisms.

2. Literature Review

Fly Ash as a Supplementary Cementitious Material, The use of fly ash as a partial replacement for Ordinary Portland Cement (OPC) has been studied extensively since the concept of high-volume fly ash concrete was formalised, with early work establishing suitable mixture proportioning,

construction practice, and long-term case histories for such systems [1]. Siddique demonstrated that high-volume Class F fly ash concrete can achieve comparable or superior long-term compressive strength relative to plain OPC concrete, albeit with slower early-age gain due to the delayed pozzolanic reaction of fly ash with calcium hydroxide [2]. These performance characteristics are reflected in specification standards such as IS 3812 (Part 1), which defines the physical and chemical requirements for pulverized fuel ash used as a pozzolana in cement, mortar, and concrete [3].

Alccofine as an Ultrafine Reactive SCM, Alccofine, an ultrafine ground granulated slag-based material, has been reported to substantially enhance early and long-term mechanical properties of concrete due to its extremely high fineness and pozzolanic reactivity. Patel and Shah found that incorporating ultrafine slag improved both compressive and flexural strength in high-strength concrete relative to control mixes [4], while Bhavsar and Panchal further reported improvements in durability parameters, including reduced permeability and enhanced resistance to aggressive exposure, when Alccofine was used as a partial cement replacement [5].

Cement Hydration and Microstructural Development, The mechanistic basis for strength gain in blended cementitious systems lies in the hydration chemistry of Portland cement and the pozzolanic reactions of SCMs, both of which have been described in detail in foundational texts on cement structure and performance [6] and on concrete microstructure more broadly [14]. Scrivener et al. reviewed advances in understanding the kinetics of Portland cement hydration, emphasising the role of nucleation and the availability of reactive silica and alumina in governing the rate and extent of hydrate formation [15]. Complementing this mechanistic understanding, Kumar et al. used Scanning Electron Microscopy and Energy Dispersive Spectroscopy to directly visualise the densification of the C-S-H matrix and the corresponding depletion of calcium hydroxide crystals in blended cement concretes, providing microstructural confirmation of pozzolanic activity [16].

Ternary and Multi-Blend Systems, Comparatively fewer studies have examined ternary combinations of SCMs with differing reactivity and particle characteristics. Vance et al. showed that ternary blends of Portland cement with limestone powder and fly ash or metakaolin produced synergistic improvements in hydration and strength development relative to binary blends, attributed to the combined filler and pozzolanic effects of the constituent materials [7]. Similarly, De Weerd et al. reported a clear synergy between fly ash and limestone powder in ternary cement systems, wherein the presence of limestone accelerated fly ash reactivity through additional nucleation sites and favourable changes in pore solution chemistry [8]. These findings support the rationale for combining fly ash, Alccofine, and dolomite powder in the present study, each contributing a distinct filler or pozzolanic mechanism.

Standardised Testing Frameworks, The mechanical characterisation of concrete incorporating SCMs is governed by well-established national and international standards. Compressive, flexural, and split tensile strength testing

procedures are specified in IS 516 [9] and IS 5816 [10], and their equivalent international counterparts ASTM C39/C39M [11], ASTM C78/C78M [12], and ASTM C496/C496M [13], which collectively provide the standardised specimen geometries and loading configurations adopted in this study.

Sustainability Drivers and Research Gap, The broader motivation for SCM-based concrete is rooted in sustainability: Damtoft et al. highlighted the cement industry's significant contribution to global CO₂ emissions and outlined pathways, including SCM substitution, for mitigating the sector's environmental impact [17]. While the individual behaviour of fly ash, Alccofine, and dolomite powder is well documented, their combined ternary use across multiple concrete grades and extended curing ages has received limited systematic investigation — a gap the present study addresses through parallel mechanical and microstructural evaluation.

3. Materials and Methodology

3.1 Fly Ash

The physical and chemical properties of the fly ash used in this study are summarised in Table 1.

Table 1: Physical and chemical properties of fly ash

Property	Typical value / range	Remarks
Colour	Grey to dark grey	Depends mainly on carbon and iron content
Particle size	Mostly < 100 μm	Generally finer than cement
Specific gravity	1.5–3.0	Commonly around 2.2–2.6
Bulk density	0.6–1.2 Mg/m^3	Lower than OPC
pH	7.2–12.6	Usually alkaline
SiO ₂	27–64%	Contributes to pozzolanic activity
Al ₂ O ₃	7–38%	Important pozzolanic constituent
Fe ₂ O ₃	1.7–33%	Influences colour and specific gravity
CaO	0.5–27%	Higher in Class C fly ash
LOI	< 5% (good quality)	Indicates unburnt carbon

3.2 Alccofine 1203

Alccofine 1203, an ultrafine ground granulated slag-based SCM, was used to enhance early-age strength and reduce permeability. Its principal properties are listed in Table 2.

Table 2: Physical and chemical properties of Alccofine 1203

Property	Typical value / range	Remarks
Specific gravity	≈ 2.8 –3.0	Depends on grade
Particle size	< 15 μm (ultrafine)	Much finer than cement
Mean particle size	≈ 4 –6 μm	High surface area
Blaine fineness	$\approx 1,200 \text{ m}^2/\text{kg}$	Very high fineness
SiO ₂	≈ 30 –35%	Contributes to pozzolanic reaction
Al ₂ O ₃	≈ 20 –25%	Promotes additional hydrates
CaO	≈ 30 –35%	Contributes to hydraulic behaviour

LOI	< 3%	Low unburnt/volatile material
Early-age strength contribution	High	Accelerates strength development

3.3 Dolomite Powder

Finely ground dolomite powder ($\text{CaMg}(\text{CO}_3)_2$) was used as a natural mineral micro-filler. Its properties are summarised in Table 3.

Table 3: Physical and chemical properties of dolomite powder

Property	Typical value / range	Remarks
Chemical formula	$\text{CaMg}(\text{CO}_3)_2$	Calcium magnesium carbonate
Specific gravity	2.8–2.9	Typically ≈ 2.85
Bulk density	1.2–1.6 g/cm ³	Depends on packing
Hardness (Mohs)	3.5–4	Relatively soft
CaO	$\approx 30.4\%$	Theoretical pure dolomite
MgO	$\approx 21.9\%$	Theoretical pure dolomite
CO ₂	$\approx 47.7\%$	Theoretical pure dolomite
Solubility in water	Very low	Practically insoluble
Filler effect	Good	Fills voids between cementitious particles

3.4 Mix Grades and Specimen Preparation

Three concrete grades- M30, M40, and M50- were proportioned to their respective target mean strengths using the ternary blend of fly ash, Alccofine 1203, and dolomite powder as partial replacements for OPC, together with locally sourced fine and coarse aggregates and potable water. For each grade, standard specimens were cast for three mechanical tests: 150 mm cubes for compressive strength, 100 × 100 × 500 mm beams for flexural strength, and 150 × 300 mm cylinders for split tensile strength. All specimens were demoulded after 24 hours and subsequently cured in water maintained at $27 \pm 2^\circ\text{C}$ until the scheduled test age of 7, 28, 56, or 90 days. Reported strength values represent the average of three specimens tested per grade, per age, and per property.

3.5 Test Methodology

The specimen type, applicable standard, and loading configuration used for each mechanical property are summarised in Table 4.

Table 4: Summary of test methods, specimens, and applicable standards

Property	Specimen	Standard	Loading
Compressive strength	150 mm cube	IS 516 / ASTM C39	Axial compression to failure
Flexural strength	100 × 100 × 500 mm beam	IS 516 / ASTM C78	Two-point (third-point) bending
Split tensile strength	150 × 300 mm cylinder	IS 5816 / ASTM C496	Diametral compression

Microstructural characterisation of the hydrated cementitious matrix was additionally carried out using Scanning Electron Microscopy (SEM) on fractured specimens obtained from the 28-day cured cubes, to examine the morphology of hydration products and the extent of portlandite consumption in the ternary-blended mixes.

4. Results

4.1 Compressive Strength

The 150 mm cube compressive strength results, averaged over three specimens per grade per age, are presented in Table 5.

Table 5: Compressive strength development with curing age

Curing Period	M30 (MPa)	M40 (MPa)	M50 (MPa)
7 Days	21	28	35
28 Days	32	42	52
56 Days	36	47	58
90 Days	38.5	50	61.5

The gain in compressive strength beyond 28 days (to 90 days) was 20.3% for M30, 19.0% for M40, and 18.3% for M50, indicating that lower-grade mixes derived a marginally larger proportional benefit from extended curing than higher-grade mixes.

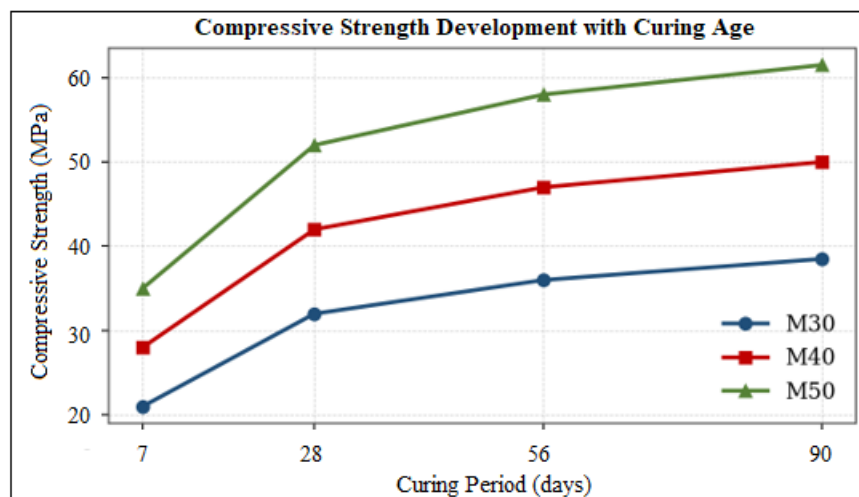


Figure 1: Compressive strength development with curing age for M30, M40, and M50 grades

4.2 Flexural Strength

The modulus of rupture obtained from third-point beam bending tests is presented in Table 6.

Table 6: Flexural strength development with curing age

Curing Period	M30 (MPa)	M40 (MPa)	M50 (MPa)
7 Days	3.2	3.7	4.1
28 Days	4.0	4.5	5.1
56 Days	4.2	4.8	5.3
90 Days	4.3	5.0	5.5

The corresponding gain beyond 28 days was 7.5% for M30, 11.1% for M40, and 7.8% for M50- appreciably smaller than the corresponding compressive strength gains, indicating that flexural strength develops more slowly with continued curing than compressive strength.

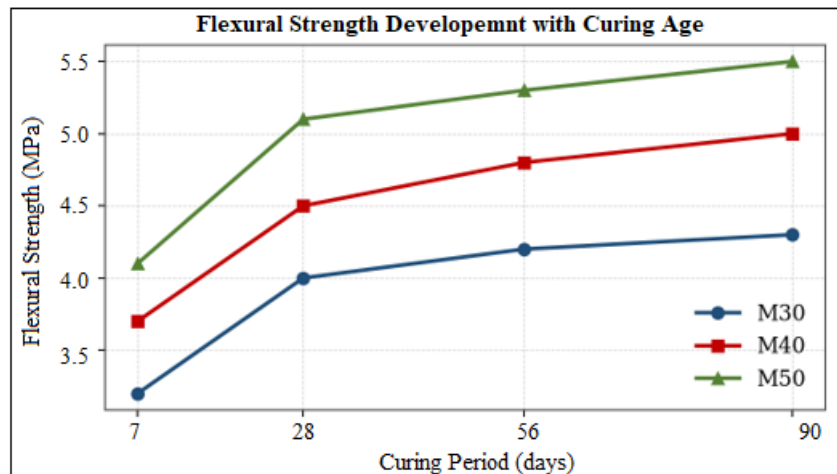


Figure 2: Flexural strength (modulus of rupture) development with curing age for M30, M40, and M50 grades.

4.3 Split Tensile Strength

Cylinder splitting tensile strength results are presented in Table 7.

Table 7: Split tensile strength development with curing age

Curing Period	M30 (MPa)	M40 (MPa)	M50 (MPa)
7 Days	1.8	2.2	2.6
28 Days	2.6	3.1	3.6
56 Days	2.9	3.4	3.9
90 Days	3.0	3.6	4.1

The corresponding gain beyond 28 days was 15.4% for M30, 16.1% for M40, and 13.9% for M50, placing the rate of split tensile strength gain between that of compressive and flexural strength.

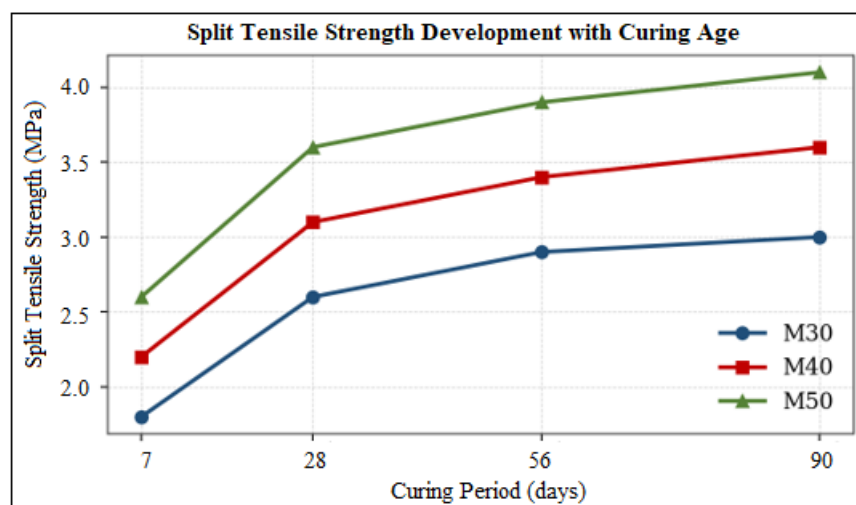


Figure 3: Split tensile strength development with curing age for M30, M40, and M50 grades.

4.4 Strength Ratios at 28 Days

Table 8 summarises the relationships between compressive, flexural, and split tensile strength at 28 days for the three grades studied.

Table 8: Strength ratios at 28 days across grades

Grade	Compressive (MPa)	Flexural (MPa)	Split Tensile (MPa)	Flex/Comp	Tensile/Comp
M30	32	4	2.6	0.125	0.081
M40	42	4.5	3.1	0.107	0.074
M50	52	5.1	3.6	0.098	0.069

Both the flexural-to-compressive and tensile-to-compressive ratios decrease consistently as the target grade increases, indicating that flexural and split tensile strength grow more slowly than compressive strength with increasing grade.

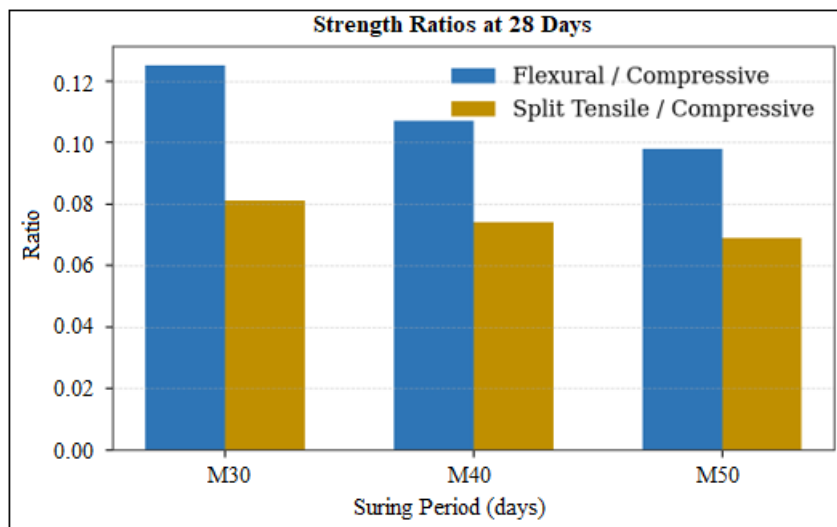


Figure 4: Flexural-to-compressive and split tensile-to-compressive strength ratios at 28 days.

4.5 Key Observations

- Compressive strength increased with grade (M30 < M40 < M50) at every curing age and continued to gain 15–20% between 28 and 90 days.
- Flexural and split tensile strength followed the same upward trend with curing age and grade, but at a slower rate than compressive strength.
- Most of the strength gain occurred by 28 days; the 56- and 90-day results showed a flatter, diminishing-returns trend for all three properties.
- Split tensile strength was consistently the lowest of the three properties, typically 6–8% of the compressive strength at 28 days.

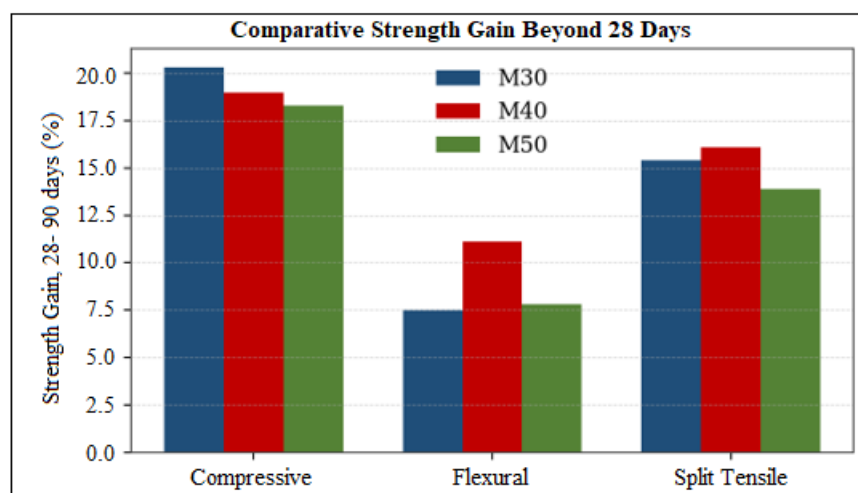


Figure 5: Comparative strength gain beyond 28 days (to 90 days) across compressive, flexural, and split tensile strength for all three grades

5. Discussion

5.1 Strength Development Mechanisms

The observed increase in compressive strength with curing age is consistent with the progressive pozzolanic reaction of fly ash and Alccofine with calcium hydroxide liberated during cement hydration, which generates additional C-S-H and C-A-S-H gel over time and densifies the cementitious matrix. The relatively larger proportional strength gain between 28 and 90 days compared with typical plain OPC concrete reflects the slower reaction kinetics of the pozzolanic components relative to cement hydration; while cement hydration is largely complete by 28 days, the pozzolanic reactions of fly ash in particular continue to contribute to strength well beyond this age. The high fineness and reactivity of Alccofine additionally accelerate early strength development, which helps explain why even the 7-day strengths were substantial relative to the 28-day values across all three grades.

The consistently slower rate of gain in flexural and split tensile strength relative to compressive strength is attributable to the fundamentally different failure mechanisms involved. Compressive strength is governed primarily by the bulk density and continuity of the hydrated paste and its bond with aggregate, both of which benefit directly from continued pozzolanic densification. Flexural and tensile failure, in contrast, are strongly influenced by the presence of micro-cracks and flaws at the paste–aggregate interface, which are less sensitive to further gel formation once a threshold density has been achieved. This is consistent with the well-established observation, further corroborated by the present results, that split tensile strength typically remains in the range of 6–8% of compressive strength for structural concrete.

5.2 Microstructural Evidence

SEM examination of the hydrated matrix in the ternary-blended mixes revealed a visible reduction in the quantity of calcium hydroxide (portlandite) crystals relative to what would typically be expected in plain OPC paste, alongside the formation of a denser, more interlocked calcium silicate hydrate (C-S-H) gel network. This observation is consistent with the pozzolanic consumption of portlandite by the reactive silica and alumina present in fly ash and Alccofine, and supports the interpretation that the observed long-term compressive strength gains are underpinned by genuine microstructural densification rather than continued cement hydration alone. The dolomite powder, being largely non-reactive, is understood to contribute primarily through improved particle packing, reducing capillary porosity and providing nucleation sites that can locally promote hydration product growth, complementing the pozzolanic action of the other two SCMs.

5.3 Practical Implications

The results indicate that the ternary fly ash–Alccofine–dolomite blend used in this study can achieve compressive strengths meeting or exceeding the target mean strengths for M30, M40, and M50 grade concrete, with continued and

appreciable strength gain up to 90 days. This behaviour has practical implications for structural design and construction scheduling: while early-age (7- and 28-day) strengths remain the basis for conventional acceptance criteria, the substantial long-term gains observed here suggest that such blended concretes may be particularly well suited to elements where later-age strength and durability, rather than very early strength, are the governing design considerations, such as mass concrete, foundations, and elements subjected to long-term sustained or long-term durability-critical exposure.

6. Conclusions

Based on the experimental and microstructural investigation of M30, M40, and M50 grade concretes incorporating a ternary blend of fly ash, Alccofine 1203, and dolomite powder as partial cement replacements, the following conclusions are drawn:

- 1) Compressive strength increased consistently with both curing age and target grade, with all three grades gaining approximately 18–20% in compressive strength between 28 and 90 days, confirming continued pozzolanic contribution well beyond the standard 28-day benchmark.
- 2) Flexural and split tensile strength followed similar upward trends with age and grade but developed at a comparatively slower rate than compressive strength, with 28–90 day gains of 7–11% and 14–16%, respectively.
- 3) Split tensile strength was consistently the lowest of the three mechanical properties evaluated, remaining at approximately 6–8% of the 28-day compressive strength across all grades, while both the flexural-to-compressive and tensile-to-compressive ratios decreased as grade increased.
- 4) SEM analysis confirmed a reduction in calcium hydroxide (portlandite) content and the formation of a denser C-S-H gel network in the ternary-blended matrix, providing direct microstructural evidence for the pozzolanic mechanisms underlying the observed long-term strength gains.
- 5) The combined use of fly ash, Alccofine, and dolomite powder offers a technically viable and potentially more sustainable alternative to conventional OPC-dominant concrete across a range of structural grades, warranting further investigation into durability performance, optimal replacement proportions, and cost-benefit analysis for field-scale application.

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