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The Effect of Mineral Additions on the Curing Process, Rheology and Durability of Heat Treated High Performance Concrete

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DEDICATION

To my beloved wife, whose unwavering support, patience, and encouragement have been my greatest source of strength. Her sacrifices and steadfast belief in me have made this journey possible.

To my dear children, Nazim and Razane, whose joy and innocence have been a constant source of inspiration. May this work serve as a reminder that perseverance and dedication pave the way to success.

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LAHMAR Seifeddine Mehdi

ABSTRACT

The demand for sustainable, high-performance construction materials has driven research into alternative cementitious materials. This study explores the potential of locally sourced Algerian andesite and calcined marl as supplementary cementitious materials (SCMs) in high-performance concrete (HPC). It examines their impact under heat-treated and non-heat-treated conditions, emphasizing pozzolanic reactivity and fresh and hardened state properties.

Comprehensive characterization using X-ray diffraction (XRD), X-ray fluorescence (XRF), scanning electron microscopy (SEM), and thermogravimetric analysis (TGA) determined the chemical composition and microstructural attributes of these materials. The Sherbrooke mix design optimized HPC formulations. Partial cement replacement was carried out at levels of 10%, 20%, and 30% by mass, using andesite and calcined marl, with natural pozzolan serving as the reference mix. Experimental evaluations covered workability, ultrasonic pulse velocity (UPV), porosity, water absorption, and compressive strength. Advanced imaging techniques, particularly computed tomography, assessed internal microstructural evolution, while statistical modeling (Design of Experiments, DOE) provided deeper insights into performance optimization.

Results confirm that andesite and calcined marl demonstrate good performance characteristics compared to the natural pozzolan reference. Fresh-state assessments showed favorable workability and stability, while hardened-state analyses revealed reduced porosity, denser microstructure, and satisfactory durability. Heat-treated samples exhibited notable early-age strength, benefiting precast and rapid construction. Non-heat-treated specimens, however, developed long-term durability through sustained pozzolanic activity. Sulfuric acid exposure confirmed the chemical resilience of these formulations, reinforcing their suitability for demanding environments.

This research advances the valorization of local mineral resources for sustainable HPC, reducing reliance on imports. The combined benefits of thermal curing and pozzolanic synergy offer a durable, eco-friendly concrete solution. By bridging material characterization, performance optimization, and practical implementation, this study provides valuable insights for academia and industry, fostering resilient, resource-efficient construction methodologies.

Keywords: High-Performance Concrete (HPC), Supplementary Cementitious Materials (SCMs), Andesite (AND), Calcined Marl (CM), Pozzolanic Reactivity, Heat Treatment, Durability.

أدى الطلب المتزايد على مواد البناء المستدامة و عالية الأداء الى تكثيف الأبحاث حول المواد الإسمنتية البديلة. تستكشف هذه الدراسة إمكانية استخدام الأنديزيت المحلي (AND) والمرل المكلس (CM) في الجزائر كمواد إسمنتية تكميلية (SCMs) في الخرسانة عالية الأداء (HPC). كما تحلل تأثيرها في ظل ظروف المعالجة الحرارية و غير المعالجة حراريا. مع التركيز على التفاعلية البوزولانية وخصائص الحالة الطازجة والمصلدة.

تم إجراء توصيف شامل لهذه المواد باستخدام حيود الأشعة السينية (XRD)، وفلورة الأشعة السينية (XEF)، والمجهر الإلكتروني الماسح (SEM)، والتحليل الحراري الوزني (TGA)، مما ساعد في تحديد التركيب الكيميائي والخصائص البنية المجهرية. كما تم تحسين تصميم الخلطة الخرسانية وفق منهجية جامعة شيربروك لتحقيق أفضل تركيبات للخرسانة عالية الأداء. تم إجراء الاستبدال الجزئي للإسمنت بمستويات 10%، 20%، و30% بالكتلة، باستخدام الأنديزيت والمرل المكلس، مع استخدام البوزولان الطبيعي كخلطة مرجعية، وشملت التقييمات التجريبية القابلية للتشغيل، وسرعة النبض فوق الصوتي (UPV)، والمسامية، وامتصاص الماء، ومقاومة الضغط. بالإضافة الى ذلك، تم استخدام تقنيات التصوير المتقدمة، ولا سيما التصوير المقطعي المحوسب، لدراسة لدراسة تطور البنية المجهرية الداخلية، بينما ساعدت النمذجة الإحصائية (تصميم (DOE)) في تعميق فهم تحسين الأداء.

أكدت النتائج أن الأنديزيت والمرل المكلس يُظهران أداءً جيداً مقارنة بالخلطة المرجعية المحتوية على البوزولان الطبيعي. أظهرت التقييمات في الحالة الطازجة قابلية للتشغيل والثبات مرضية، بينما كشفت التحليلات في الحالة المصلدة عن انخفاض في المسامية، وزيادة كثافة البنية المجهرية، وتطوير ديمومة مناسبة. كما أظهرت العينات المعالجة حراريا قوة مبكرة ملحوظة، مما يجعلها مناسبة للخرسانة مسبقة الصب والتشييد السريع. من ناحية أخرى، طورت العينات غير المعالجة حراريا متانة طويلة الأمد بفضل النشاط البوزولاني المستدام، وأكد التعرض لحمض الكبريت مقاومة هذه التركيبات الكيميائية، مما يعزز ملاءمتها للبيئات القاسية.

تسهم هذه الدراسة في تعزيز استغلال المواد المعدنية المحلية لإنتاج خرسانة عالية الأداء مستدامة، مما يقلل الاعتماد على الواردات. إن الجمع بين المعالجة الحرارية والتآزر البوزولاني يوفر حلاً خرسانياً متينًا وصديقًا للبيئة. ومن خلال الربط بين توصيف المواد، وتحسين الأداء، والتطبيق العملي، تقدم هذه الدراسة رؤى قيمة للأواسط الأكاديمية والصناعية، مما يسهم في تطوير منهجيات بناء أكثر كفاءة واستدامة.

الكلمات المفتاحية: الخرسانة عالية الأداء (HPC)، المواد الإسمنتية التكميلية (SCMs)، الأنديزيت (AND)، المرل المكلس (CM)، التفاعيلة البوزولانية، المعالجة الحرارية، المتانة.

RÉSUMÉ

La demande croissante de matériaux de construction durables et performants a stimulé la recherche sur des alternatives cimentaires. Cette étude évalue le potentiel de l'andésite et de la marne calcinée d'Algérie en tant que matériaux cimentaires supplémentaires (SCMs) dans le béton à haute performance (HPC), en analysant leur réactivité pouzzolanique et leur influence sous traitement thermique et non thermique.

La caractérisation inclut la diffraction des rayons X (XRD), la fluorescence des rayons X (XRF), la microscopie électronique à balayage (SEM) et l'analyse thermogravimétrique (TGA) pour identifier la composition chimique et la microstructure des matériaux. La formulation des mélanges HPC est optimisée selon la méthodologie de Sherbrooke. Le remplacement partiel du ciment a été réalisé aux niveaux de 10%, 20% et 30% en masse, en utilisant l'andésite et la marne calcinée, avec la pouzzolane naturelle servant de béton témoin. Les essais expérimentaux comprennent l'évaluation de la maniabilité, de la vitesse des impulsions ultrasonores (UPV), de la porosité, de l'absorption d'eau, ainsi que de la résistance à la compression. L'évolution microstructurale interne est analysée par tomographie assistée par ordinateur, et l'optimisation des performances est approfondie via la modélisation statistique par plan d'expériences (DOE).

Les résultats confirment que l'andésite et la marne calcinée présentent de bonnes performances par rapport au béton témoin à base de pouzzolane naturelle. À l'état frais, elles montrent une maniabilité et une stabilité satisfaisantes. À l'état durci, elles réduisent la porosité, densifient la microstructure et développent une durabilité appropriée. Le traitement thermique permet un gain notable de résistance mécanique précoce, bénéfique pour les éléments préfabriqués et la construction rapide. Les échantillons non traités thermiquement développent une durabilité à long terme grâce à une activité pouzzolanique prolongée. L'exposition à l'acide sulfurique confirme leur résistance chimique, validant leur utilisation dans des environnements agressifs.

Cette étude valorise les ressources minérales locales pour un HPC durable, limitant la dépendance aux matériaux importés. La synergie entre traitement thermique et réactivité pouzzolanique offre une solution béton performante et écologique. En combinant caractérisation, optimisation et application industrielle, cette recherche ouvre la voie à des pratiques constructives plus durables et efficientes.

Mots-clés : Béton à haute performance (HPC), Matériaux cimentaires supplémentaires (SCMs), Andésite (AND), Marne calcinée (CM), Réactivité pouzzolanique, Traitement thermique, Durabilité.

NOMENCLATURE: SYMBOLS, ABBREVIATIONS, AND NOTATIONS

Chemical Formulae and Notations

Symbol	Full Chemical Name	Common Engineering Term	
CO ₂	Carbon Dioxide	Carbonation Agent	
SiO ₂	Silicon Dioxide	Silica / Quartz	
Al ₂ O ₃	Aluminum Oxide	Alumina	
Fe ₂ O ₃	Iron (Iii) Oxide	Ferric Oxide	
CaO	Calcium Oxide	Quicklime / Free Lime	
MgO	Magnesium Oxide	Magnesia	
K ₂ O	Potassium Oxide	Potash / Alkali Oxide	
Na ₂ O	Sodium Oxide	Soda / Alkali Oxide	
SO ₃	Sulfur Trioxide	Sulfate Component	
Cl-	Chloride Ion	Free Chloride	
СН	Calcium Hydroxide	Portlandite	
residual	Free Calcium Ions	Soluble Lime	
Ca ²⁺			
OH- ion	Hydroxide Ion	Alkaline Cement Solution	
C-S-H	Calcium Silicate Hydrate	Main Hydration Product In Cement	
С-А-Н	Calcium Aluminate Hydrate	Cementitious Hydrate (Aluminate Phase)	
C-A-S-H	Calcium Alumino-Silicate Hydrate	Hydrated Pozzolanic Phase	
Ca(OH) ₂	Calcium Hydroxide	Portlandite	
NaOH	NaOH Sodium Hydroxide Caustic Soda		
Na ₂ SiO ₃	Sodium Silicate	Water Glass / Silicate Solution	
CaCl ₂	Calcium Chloride	Concrete Accelerator	
AFt	Ettringite Phase	Sulfoaluminate Hydrate	
AFm	Monosulfate Phase	Calcium Aluminate Monosulfate	
C ₂ S	Dicalcium Silicate	Belite	

C ₃ S	Tricalcium Silicate	Alite
C ₃ A	Tricalcium Aluminate	Aluminate Phase
C ₄ AF	Tetracalcium Aluminoferrite	Ferrite Phase

Units and Measurements

Symbol	Description	Units
W/B	Water-to-Binder Ratio	Dimensionless
W/C	water-to-cement Ratio	Dimensionless
ρ	The Bulk Density, Specific Gravity	g/cm³
ρ_bulk	Absolute Density	g/cm³
SSB	Specific Surface Area (Blaine)	cm ² /g
T	Temperature	°C
SD	Standard Deviation	Dimensionless
CoV	Coefficient of Variation	%
EW	Evaporated Water	%
UPV	Ultrasonic Pulse Velocity	m/s
WAC	Water Absorption Capacity	%
P	Porosity	%
CS-D	Compressive Strength at X days	MPa
CS-60	S-60 Compressive Strength at 60 Days Post Sulfuric Acid	
Acid	Immersion	
CS-60	Percentage Strength Loss After Acid Exposure	%
Red.		
SAI	Strength Activity Index	Dimensionless

Technical Abbreviations

Abbreviation	Full Term
HPC	High-Performance Concrete
SCM	Supplementary Cementitious Materials
OPC	Ordinary Portland Cement
C	Cement

CEM I	Portland Cement (Pure)
AND	Andesite
NM	Naturel Marl
CM	Calcined Marl
NPZ	Natural Pozzolan
UHPC	Ultra-High-Performance Concrete
SCC	Self-Consolidating Concrete , Self-Compacting
	Concrete
OC	Ordinary Concrete
EC	Exceptional Concrete
HT	Heat-Treated
NT	Non-Heat-Treated
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence
SEM	Scanning Electron Microscopy
TGA	Thermogravimetric Analysis
DTA	Differential Thermal Analysis
DSC	Differential Scanning Calorimetry
EDX	Energy Dispersive X-Ray Spectroscopy
TEM	Transmission Electron Microscopy
AFM	Atomic Force Microscopy
DOE	Design Of Experiments
RSM	Response Surface Methodology
CT	X-Ray Computed Tomography
ANOVA	Analysis Of Variance
GGBS	Ground Granulated Blast Furnace Slag
RCA	Recycled Concrete Aggregates
RHA	Rice Husk Ash
MK	Metakaolin
SF	Silica Fume
FA	Fly Ash
SP	Superplasticizer
S	Sand

ITZ	Interfacial Transition Zone
ASR	Alkali-Silica Reaction
TAS	Total Alkali-Silica
LCA	Life Cycle Assessment
PCMs	Phase Change Materials
NDT	Non-Destructive Testing
HRWR	High-Range Water-Reducing Admixture
3D	Three-Dimensional
3DPC	3d-Printed Concrete
СР	Concrete Printing
ASTM	American Society For Testing And Materials
EN	European Norm
ACI	American Concrete Institute
NA	Algerian Standard
N	North
E	East
W	West
S	South
N/A	Not Available

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GENERAL INTRODUCTION

C H A P T B R

1

CHAPTER -1:

General Introduction: "Innovative Strategies for Enhancing High-Performance Concrete: Research Scope and Objectives"

1 General Introduction

1.1 Research Background

The rapid expansion of infrastructure development and the increasing demand for durable and sustainable construction materials have propelled high-performance concrete (HPC) to the forefront of modern engineering research. HPC is distinguished by its superior mechanical properties, extended durability, and reduced permeability, making it a preferred choice for critical infrastructure applications [1], [2]. A key factor in achieving these properties is the incorporation of supplementary cementitious materials (SCMs), which enhance concrete performance through pozzolanic activity and microstructural refinement. Traditional SCMs, such as silica fume, fly ash, and natural pozzolans, have been extensively studied, but alternative local resources remain underutilized [3], [4].

The cement industry is responsible for approximately 8% of global CO₂ emissions, necessitating urgent measures to reduce its environmental footprint [5]. One effective approach is to replace a portion of clinker with locally available SCMs, thereby reducing energy consumption and carbon emissions associated with cement production. Algeria, rich in mineral resources, offers a promising avenue for such sustainable alternatives. Andesite and calcined marl, abundant in the region, have shown potential as SCMs due to their chemical composition and pozzolanic reactivity [6], [7]. Their integration into HPC formulations could significantly enhance sustainability while maintaining high performance.

Andesite, a volcanic rock with a high silica content, exhibits strong pozzolanic behavior, improving concrete's mechanical properties, durability, and resistance to sulfate attack and freeze-thaw cycles [8], [9]. Its fine particle size distribution optimizes hydration kinetics, contributing to enhanced long-term strength and microstructural refinement [10]. Similarly, calcined marl, obtained through the thermal activation of marl deposits, has demonstrated notable pozzolanic reactivity, forming additional calcium silicate hydrate (C-S-H) phases that

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enhance compressive strength and durability [11], [12]. These materials provide an eco-friendly alternative to conventional SCMs while leveraging Algeria's natural resources for sustainable construction [13], [14].

Despite these advantages, comprehensive studies on the characterization, optimization, and practical application of andesite and calcined marl in HPC remain limited. Most existing research has focused on widely used SCMs, leaving a critical knowledge gap regarding the effectiveness of these local materials. Additionally, their performance under thermal curing conditions, which is known to accelerate hydration and improve early-age strength, requires further investigation [15], [16].

Thermal curing plays a crucial role in enhancing the performance of high-performance concrete by accelerating hydration reactions and improving microstructural development. Heat treatment is particularly beneficial in optimizing early-age strength gain, refining pore structure, and enhancing long-term durability [17]. Research has shown that elevated temperature curing promotes the formation of additional C-S-H phases, leading to a denser and more refined matrix, which significantly improves mechanical properties and durability under aggressive environmental conditions [18]. However, the effectiveness of heat treatment varies depending on the composition of the cementitious system, the type and proportion of SCMs used, and the specific curing regime applied. This study aims to analyze the effects of heat treatment on HPC incorporating andesite and calcined marl, comparing its performance against non-heat-treated HPC to establish clear benefits and potential trade-offs in its application [19].

To address these gaps, this research integrates an extensive experimental approach, employing advanced analytical techniques for material characterization and performance evaluation. Characterization of andesite and calcined marl is conducted using X-ray diffraction (XRD), X-ray fluorescence (XRF), and scanning electron microscopy (SEM) to determine their chemical composition, mineralogical structure, and microstructural morphology [20], [21]. Additionally, thermogravimetric analysis (TGA) is employed to assess the thermal stability and decomposition behavior of these materials, providing insights into their composition and reactivity [22].

To evaluate the pozzolanic activity of andesite and calcined marl, chemical and mechanical testing methods are applied, including lime consumption tests and strength activity index measurements, ensuring a rigorous assessment of their reactivity and contribution to cement hydration [23], [24]. These analyses form the foundation for optimizing HPC mix designs.

The optimization of HPC formulations incorporates the Sherbrooke method, a systematic approach to mix proportioning that balances workability, strength, and durability while ensuring compatibility with locally available materials [25]. Furthermore, the impact of thermal curing on the hydration kinetics and performance of HPC is examined, with a focus on its influence on early-age strength and microstructural development [26].

The evaluation of fresh and hardened concrete properties follows standardized testing procedures. Workability, setting time, and rheological properties are assessed to determine the effects of Mineral Additions on fresh-state behavior, while compressive strength, flexural strength, and permeability tests provide insights into hardened-state performance [8], [27]. To further analyze the internal microstructure and durability characteristics, tomography imaging is utilized, offering a detailed visualization of pore structure and crack propagation within HPC [28].

To ensure a robust and scientifically rigorous approach, the research employs Design of Experiments (DOE) methodology using JMP software, facilitating statistical optimization and response surface analysis of mix formulations. DOE enables the identification of optimal mixture proportions while minimizing experimental variability, ensuring the reliability and reproducibility of results [29], [30].

1.2 Significance of the Study

The construction sector is a major consumer of natural resources and energy, necessitating sustainable alternatives to conventional building materials. The integration of locally sourced SCMs into HPC formulations offers multiple advantages, including cost reduction, enhanced material efficiency, and improved environmental sustainability. Andesite, a fine-grained volcanic rock with high silica content, has demonstrated promise as a pozzolanic material capable of enhancing HPC properties by improving compressive strength and reducing water permeability [9]. Furthermore, research indicates that andesite-based concrete exhibits superior resistance to sulfate attack and freeze-thaw cycles, making it suitable for harsh environmental conditions [10].

Similarly, calcined marl, a thermally activated material derived from marl deposits, has been identified as a promising SCM due to its pozzolanic activity. The thermal activation process enhances the reactivity of calcined marl, facilitating the formation of calcium silicate hydrate (C-S-H) gel, which contributes to improved mechanical performance and durability [12], [13]. Given its chemical stability and favorable microstructural characteristics, calcined marl

presents a viable option for HPC applications, particularly in regions with abundant marl resources.

This research is significant as it provides a comprehensive evaluation of the performance of andesite and calcined marl in HPC, with a particular focus on their pozzolanic activity and the impact of thermal treatment on concrete properties. The findings have practical implications for sustainable construction, material cost optimization, and the promotion of regional mineral resources in Algeria's construction industry [14], [15].

1.3 Thesis Aims and Objectives

The primary objective of this research is to evaluate the feasibility of utilizing Algerian andesite and calcined marl as supplementary cementitious materials in HPC. This investigation focuses on their pozzolanic properties, impact on mechanical and durability characteristics, and performance under thermal curing conditions. The ultimate goal is to develop optimized HPC formulations that enhance both sustainability and efficiency in concrete production.

The specific objectives of this study are:

- Characterization of mineral additions: Perform detailed physicochemical and microstructural analyses of andesite and calcined marl using advanced characterization techniques such as XRD, XRF, and SEM to assess their composition and pozzolanic reactivity.
- ♣ Assessment of pozzolanic activity: Evaluate the reactivity of these materials using standardized chemical and mechanical testing to determine their effectiveness in cementitious applications.
- ♣ Optimization of HPC mix designs: Develop optimized mix formulations incorporating andesite and calcined marl based on experimental results.
- ♣ Evaluation of fresh and hardened properties: Investigate the influence of mineral additions on workability, setting behavior, early-age strength, and long-term mechanical performance, including compressive strength, permeability, and durability.
- ♣ Investigation of thermal curing effects: Analyze the effects of elevated temperature curing on hydration kinetics, microstructure evolution, and overall HPC performance.
- ♣ Comparative analysis with conventional SCMs: Benchmark the performance of andesite and calcined marl against widely used pozzolans, such as natural pozzolan from Benisaf, to validate their practical applications in HPC. Additionally, statistical optimization techniques, specifically the Design of Experiments (DOE) methodology, will be

employed to analyze key performance factors, optimize mixture proportions, and ensure reliability in experimental findings.

1.4 Thesis Structure

This thesis is structured to provide a systematic exploration of andesite and calcined marl as Mineral additions in HPC, ensuring a logical progression from theoretical concepts to experimental findings and practical applications. The document is organized as follows:

- ♣ Chapter 1 General Introduction: Outlines the research background, significance of the study, research aims and objectives, and thesis organization.
- ♣ Chapter 2 Literature Review: Presents a comprehensive review of relevant studies on high-performance concrete, supplementary cementitious materials, pozzolanic activity, thermal curing, and material characterization techniques.
- ♣ Chapter 3 Materials and Experimental Methods: Details the methodology for material characterization, mix design development, and experimental procedures used to assess fresh and hardened concrete properties.
- ♣ Chapter 4 Results and Discussion: Analyzes experimental results related to the pozzolanic activity, mechanical properties, durability, and the effects of thermal curing on HPC performance.
- Chapter 5 Conclusion and Recommendations: Summarizes key findings, discusses practical implications, and provides recommendations for future research and applications.

This research is expected to make a significant contribution to the advancement of sustainable high-performance concrete by integrating local mineral resources, particularly andesite and calcined marl, into thermally cured formulations. The outcomes of this study will serve as a scientific foundation for optimizing HPC properties, improving durability, and enhancing early-age strength through controlled heat treatment. By reducing dependence on traditional SCMs and utilizing regionally abundant materials, this research promotes eco-efficient and cost-effective construction practices. Furthermore, by systematically evaluating the comparative performance of heat-treated and non-heat-treated HPC, this study aims to provide valuable insights into the benefits, challenges, and practical applications of thermal curing in sustainable concrete technology. Ultimately, these findings will contribute to global efforts in minimizing the environmental footprint of cement-based materials while enhancing infrastructure resilience and longevity.

H A P T LETTERATURE REVIEW 图 R

CHAPTER -2:

LETTERATURE REVIEW

2 LETTERATURE REVIEW

2.1 High-Performance Concrete (HPC): Characteristics and Evolution

2.1.1 Evolution and Comparative Analysis of HPC

2.1.1.1 Historical Development and Key Advances in HPC

The evolution of High-Performance Concrete (HPC) represents a paradigm shift in concrete technology, driven by the need for materials that surpass traditional concrete in strength, durability, and overall performance. Emerging in the 1960s, the development of high-strength concrete initially gained traction in Chicago, where innovative designers and concrete producers collaborated to create concrete capable of doubling the compressive strength of conventional mixes. These early advancements relied on reducing the water-to-binder (W/B) ratio and incorporating emerging water reducers and supplementary materials like fly ash, resulting in compressive strengths of 45–60 MPa, a significant improvement over the standard 15–30 MPa used at the time [31].

The introduction of superplasticizers in the late 1960s and 1970s marked a turning point. These admixtures enabled substantial reductions in W/B ratios while maintaining workability, setting the stage for further advancements in mix design. Early applications of superplasticizers primarily aimed to enhance fluidity on-site, but their role as high-range water reducers soon became evident, allowing for compressive strengths exceeding 100 MPa [31]. Concurrently, silica fume—a byproduct of silicon and ferrosilicon production—emerged as a revolutionary supplementary cementitious material. Its fine particle size and pozzolanic properties significantly improved the microstructure of concrete, enhancing durability and strength. By the 1980s, silica fume had become an essential component in high-strength concrete, enabling compressive strengths in the range of 100–150 MPa [32], [33].

The 1990s ushered in the era of Ultra-High-Performance Concrete (UHPC), characterized by compressive strengths exceeding 150 MPa and an ultra-dense matrix. UHPC introduced remarkable durability and resistance to environmental degradation, facilitated by advanced curing methods and the inclusion of fibers to mitigate brittleness. Innovations such as high-energy mixing and tailored fiber reinforcement further enhanced mechanical properties and expanded the applications of both HPC and UHPC in infrastructure and high-rise construction [34], [35].

Self-consolidating concrete (SCC), another innovation of this period, eliminated the need for mechanical vibration during placement, revolutionizing construction by reducing labor and ensuring superior

surface finishes [36], [37]. These developments highlighted the versatility of HPC in meeting diverse structural demands while addressing challenges related to workability and placement.

A defining feature of HPC's evolution is its adaptability to address modern construction challenges, including sustainability. The integration of fiber reinforcement, using materials such as steel, polypropylene, and glass, has significantly improved crack resistance and post-cracking behavior, making HPC particularly suitable for seismic zones and structures exposed to dynamic loads [38], [39]. Meanwhile, researchers continue to explore innovative applications of supplementary cementitious materials and cutting-edge admixtures to reduce the environmental footprint of concrete production [40], [41].

The insights of Aïtcin [31] underscore the importance of meticulous material selection and incremental advancements in overcoming technological barriers. The gradual reduction of W/B ratios through the development of superplasticizers and the adoption of silica fume illustrates the interplay of innovation and practice in advancing HPC. These efforts have enabled the production of concrete with rock-like strength and durability, capable of forming slender, efficient, and aesthetically pleasing structures.

Today, HPC continues to play a pivotal role in modern construction, offering solutions that combine structural performance, durability, and sustainability. Its applications in high-rise buildings, bridges, and precast elements reflect decades of research and innovation, ensuring its relevance in addressing the demands of the built environment.

2.1.1.2 Comparative Analysis with Conventional Concrete

The comparative analysis of HPC with conventional concrete reveals significant differences in mechanical properties, durability, and overall performance. Conventional concrete typically exhibits compressive strengths in the range of 20 to 40 MPa, while HPC can achieve strengths exceeding 80 MPa, and UHPC can reach values as high as 150 MPa or more [35], [42] . This substantial increase in strength allows for the design of slender structural elements, reducing the overall material consumption and enhancing the sustainability of construction projects [43].

In terms of durability, HPC demonstrates superior resistance to environmental factors such as freeze-thaw cycles, chloride penetration, and chemical attacks. The dense microstructure of HPC, achieved through the careful selection of materials and mix design, results in lower permeability and reduced susceptibility to deterioration [40], [44]. Studies have shown that HPC can significantly outperform conventional concrete in terms of service life, particularly in harsh environments, making it an ideal choice for infrastructure projects such as bridges and tunnels.

Moreover, HPC exhibits enhanced workability and flow characteristics, which facilitate easier placement and consolidation, especially in complex formwork [36], [45]. The use of superplasticizers and other chemical admixtures in HPC formulations allows for higher fluidity without compromising strength, which is particularly beneficial in applications requiring intricate detailing [46], [47]. This contrasts with conventional concrete, which often requires extensive vibration to achieve adequate compaction, leading to potential issues with segregation and air entrapment [36], [37].

The application of HPC has also been shown to improve the overall performance of structures under dynamic loading conditions. Research indicates that HPC can provide better energy absorption and ductility compared to conventional concrete, making it more suitable for seismic applications [39], [48]. The incorporation of fibers into HPC mixes further enhances its impact resistance and crack control, addressing one of the primary concerns associated with traditional concrete [38], [39].

In summary, the evolution of HPC has led to a material that not only surpasses conventional concrete in terms of mechanical properties and durability but also offers enhanced workability and performance in challenging environments. The ongoing research into the effects of mineral additions and innovative mix designs continues to push the boundaries of what is possible with HPC, ensuring its relevance in modern construction practices[40], [41].

Table 2.1: Classification of concrete types based on 28-day compressive strength criteria [49].

Type of Concrete	28 d Compressive Strength (MPa)
Ordinary Concrete (OC)	20–50
High Performance Concrete (HPC)	50–150
Ulta-High-Performance Concrete (UHPC)	100–150
Exceptional Concrete (EC)	>150

Table 2.2: Comparative analysis of conventional concrete (CC), high-performance concrete (HPC), and ultra-high-performance concrete (UHPC) based on key properties and material composition [50].

Parameter	CC	HPC	UHPC
Compressive Strength (MPa)	< 50	≈ 100	> 200
W/Binder	> 0.5	≈ 0.3	< 0.2
Chemical Admixture	Not necessary	SP necessary	SP essential
Mineral Addition	Not necessary	FA or SF current	SF or ultra-fine essential
Fibres	Beneficial	Beneficial	Essential
Air Entraining Agent	Necessary	Necessary	Not necessary
Processing	Conventional	Conventional	Thermal treatment plus pressure
Chloride Diffusion Coefficient (steady state) (x10 ⁻¹² m ² /s)	1	0.6	0.02

2.1.2 Components and Design Principles of HPC

2.1.2.1 Cementitious Materials and SCMs in HPC

High-Performance Concrete (HPC) is distinguished by its outstanding mechanical strength and durability, attributes that are strongly influenced by the selection of cementitious and supplementary cementitious materials (SCMs). While Portland cement continues to serve as the primary binder, the incorporation of SCMs such as fly ash, ground granulated blast-furnace slag (GGBS), and silica fume is integral to enhancing the performance of HPC. These materials improve workability, lower permeability, and increase resistance to harsh environmental conditions [51], [52].

As illustrated in Figure 2.1, SCMs exhibit a wide range of particle sizes and specific surface areas, influencing their reactivity and effect on concrete properties. Finer materials, such as silica fume, offer higher pozzolanic activity, while coarser SCMs like fly ash contribute to long-term strength development.

Figure 2.2 further compares the particle size distribution of ASTM Type I Portland cement, high-calcium and low-calcium fly ash, and condensed silica fume. The curves highlight the significantly finer nature of silica fume, which enhances the densification of the cementitious matrix. The varying fineness of these materials directly affects hydration kinetics and the overall microstructure of HPC.

Specific Surface Area, m²/kg

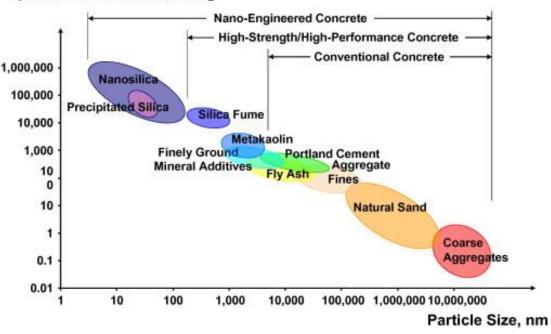


Figure 2.1: Particle size distribution and specific surface area of cementitious materials and supplementary cementitious materials (SCMs) used in high-performance concrete (HPC) [53].

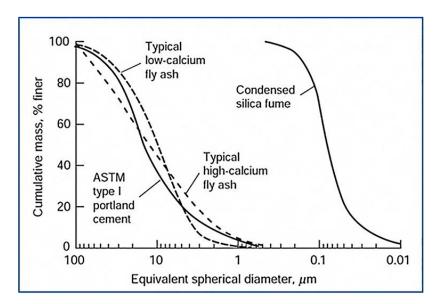


Figure 2.2: Particle size distribution of ASTM Type I Portland cement, fly ash (low-calcium and high-calcium), and condensed silica fume [2].

The use of locally sourced mineral additions, including natural and artificial pozzolans, has proven to be an effective approach for enhancing the properties of HPC. Natural pozzolans, such as volcanic ash, improve pozzolanic activity and reduce the heat of hydration, while artificial pozzolans like metakaolin and recycled industrial by-products significantly contribute to mechanical strength and durability [54], [55]. Utilizing these local materials not only fosters sustainability in concrete production but also strengthens regional economies by leveraging readily available resources.

As shown in Figure 2.3, the ternary CaO–Al₂O₃–SiO₂ diagram illustrates the chemical composition of various cementitious materials, highlighting their variability in oxide content and reactivity. Additionally, Figure 2.4 presents the phase distribution of hydration products in Portland cement–SCM blends, depicting key hydrates such as C-S-H, C-A-S-H, portlandite, strätlingite, and AFt/AFm phases, which influence microstructural development and long-term durability. These figures emphasize the role of SCMs in optimizing HPC performance while promoting sustainability through local material utilization.

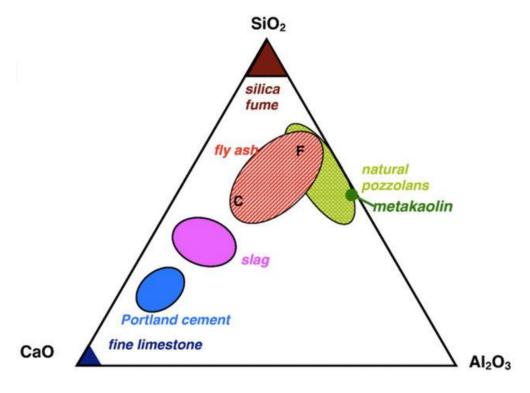


Figure 2.3: Ternary CaO–Al₂O₃–SiO₂ diagram depicting the chemical composition of various cementitious materials, including Portland cement, limestone, slag, silica fume, metakaolin, and Class F and Class C fly ash [56].

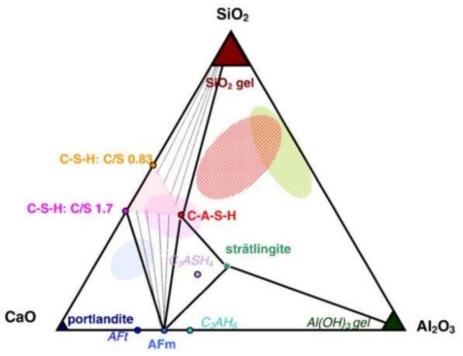


Figure 2.4: Phase distribution of hydration products in Portland cement–SCM blends within the H₂O–CaO–Al₂O₃–SiO₂ system, illustrating key hydrate phases such as C-S-H, C-A-S-H, portlandite, strätlingite, and AFt/AFm phases [56].

2.1.2.2 Aggregate Selection and Particle Distribution

The selection and optimization of aggregates are critical in ensuring the effective design and performance of High-Performance Concrete (HPC). Key factors such as the type, size, and gradation of aggregates play a significant role in determining the mechanical strength, workability, and durability of the concrete. Coarse aggregates, which constitute approximately 70–80% of the total concrete volume, are particularly important for providing structural integrity and enhancing the overall strength of the mixture [57]. Research has established that well-graded aggregates contribute to improved packing density, reduce void spaces, and enhance flowability, all of which are essential for achieving optimal performance in HPC [58].

The physical and mechanical characteristics of aggregates, including their shape and surface texture, are also crucial in influencing the bond between the cement paste and the aggregate. Angular aggregates, due to their interlocking capabilities, provide superior compressive strength compared to rounded aggregates. Additionally, optimizing the particle size distribution of aggregates is vital for achieving desirable rheological properties, minimizing the water-to-cement ratio, and improving the concrete's durability by reducing permeability.

In summary, the careful selection and precise optimization of aggregates are fundamental to enhancing the mechanical performance, workability, and durability of HPC. These considerations are indispensable in ensuring that HPC satisfies the stringent performance criteria required for contemporary construction applications.

Table 2.3: Effect of aggregate properties on the performance of high-performance concrete (HPC).

Aggregate Property	Description	Impact on HPC
Type (Coarse vs. Fine)	Coarse aggregates (~70–80% of volume) provide structural integrity.	C ,
	Fine aggregates influence workability.	durability.
Particle Size Distribution	Well-graded aggregates improve packing density and reduce void spaces	Enhances flowability and mechanical properties
Shape	Angular aggregates provide better interlocking compared to rounded ones.	1
Surface Texture	Rough textures increase the bond strength between paste and aggregate	Enhances overall mechanical strength
Gradation	Continuous gradation reduces voids and improves packing density.	Optimizes workability and minimizes permeability.

2.1.2.3 Chemical Admixtures for HPC Performance

Chemical admixtures play a vital role in enhancing the performance characteristics of High-Performance Concrete (HPC), including its workability, mechanical strength, and durability. These admixtures are generally classified into categories such as water-reducing agents, superplasticizers, air-entraining agents, and specialized admixtures, including shrinkage-reducing and corrosion-inhibiting agents. Water-reducing agents, particularly superplasticizers, are instrumental in achieving the low water-cement ratios required for high-strength concrete while maintaining adequate workability, a crucial parameter in HPC production [59].

As illustrated in Figure 2.5, plasticizers function by adsorbing onto cement particle surfaces, leading to the dispersion of particle flocs and the release of entrapped water. This mechanism significantly enhances fluidity, ensuring uniform hydration and improved rheological properties in HPC [60].

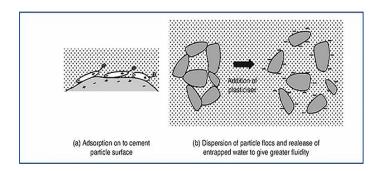


Figure 2.5: Schematic illustration of the mechanism of plasticizers in cementitious systems: (a) adsorption onto cement particle surfaces and (b) dispersion of particle flocs with the release of entrapped water, enhancing fluidity [60].

Recent technological advancements have underscored the importance of superplasticizers, especially polycarboxylate ethers, in improving both the flowability and compressive strength of concrete. These admixtures facilitate significant reductions in water content without compromising the desired performance, making them indispensable in the design of HPC mixtures. Furthermore, air-entraining agents contribute to enhanced durability by creating microscopic air voids within the concrete matrix, which help alleviate internal pressures caused by freeze-thaw cycles, thus ensuring the material's resilience in harsh environments.

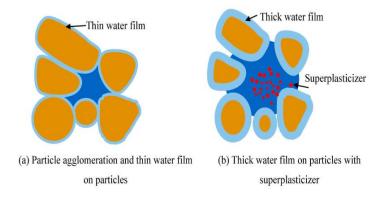


Figure 2.6: Effect of superplasticizer on particle dispersion: (a) particle agglomeration with a thin water film in the absence of superplasticizer and (b) improved dispersion with a thick water film due to superplasticizer action [61].

In conclusion, the thoughtful selection and application of chemical admixtures are fundamental to improving HPC's mechanical and durability properties. Furthermore, these advancements align with sustainable construction practices by increasing the lifespan of concrete structures and reducing the need for maintenance, thereby contributing to environmentally responsible engineering solutions.

Table 2.4: Chemical Admixtures and Their Effects on HPC Performance.

Admixture Type	Purpose	Effects on HPC		
Superplasticizers	Enhance workability while maintaining	Enable significant		
	a low water content.	reduction in water		
		usage, resulting in		
		improved strength and		
		durability. Facilitate		
		self-compacting		
		concrete production.		
Air-Entraining Agents	Create microscopic air bubbles within	Improve resistance to		
	the concrete mix.	freeze-thaw cycles and		
		increase durability in		
		cold climates by		
		allowing room for		
		water expansion.		
Accelerators	Speed up the cement hydration process.	Reduce setting time		
		and boost early		
		strength development,		
		particularly useful in		
		cold environments or		
		rapid construction		
		scenarios.		
Retarders	Delay the cement hydration process.	Prolong setting time to		
		enhance workability,		
		especially in hot		

> weather or for complex concrete placements.

reinforcement **Corrosion Inhibitors** Protect steel from Extend the service life

corrosion.

of reinforced concrete structures by reducing

the risk of corrosion.

Shrinkage-Reducing Agents Minimize drying shrinkage and the Reduce the likelihood

associated cracking risk.

shrinkage-induced cracks, enhancing the

structural integrity of concrete large

elements.

Water-Reducing Admixtures Decrease the amount of water required Improve concrete

for a workable mix.

strength and durability by lowering the water-

to-cement ratio while

desired maintaining

workability.

Viscosity-Modifying Agents Adjust the viscosity of the concrete mix Reduce segregation

to improve stability.

uniformity, mix

> particularly selfin

and bleeding, ensuring

compacting

or

underwater concreting.

2.1.2.4 Mixing Methods, Water Content, and Quality Control

The production of High-Performance Concrete (HPC) depends critically on the choice of mixing methods, careful management of water content, and the implementation of rigorous quality control measures. The mixing technique is a determining factor in achieving a uniform and consistent concrete mixture, which directly influences the mechanical properties and longterm durability of the material. Commonly employed methods, including batch mixing,

continuous mixing, and high-shear mixing, are tailored to meet specific HPC production needs. Among these, high-shear mixing is particularly advantageous for dispersing chemical admixtures and ensuring a homogeneous material distribution, which is essential for optimizing HPC's performance.

Water content is another key variable that significantly affects HPC's workability and mechanical strength. A lower water-to-cement ratio is crucial for enhancing both strength and durability; however, this often results in reduced workability. Superplasticizers address this limitation by enabling a reduction in water content while maintaining the required workability, thereby facilitating the production of high-strength concrete. Recent research has further demonstrated that optimizing water content not only enhances compressive strength but also improves resistance to chloride ion penetration, a critical factor for ensuring durability in harsh environmental conditions [62].

The assurance of quality during the mixing process is vital for meeting the defined performance specifications of HPC. This includes meticulous monitoring of mix consistency, precise proportioning of ingredients, and effective integration of chemical admixtures. Advanced technologies, such as machine learning and statistical modeling, are increasingly being employed to predict and refine HPC properties. These innovations allow for consistent production of high-quality concrete that adheres to stringent performance standards.

In summary, the successful production of HPC requires the seamless integration of advanced mixing techniques, optimized water content, and comprehensive quality control protocols. Collectively, these factors ensure that HPC achieves superior mechanical properties and durability, making it an indispensable material for complex and demanding construction applications.

2.1.2.5 Mix Proportioning, Design, and Optimization Techniques

The process of mix design focuses on determining the most appropriate proportions of cement, aggregates, water, and admixtures to achieve desired performance characteristics, including strength, workability, and durability [63]. A well-conceived mix design not only enhances the mechanical performance of concrete but also ensures its durability across a range of environmental conditions over time.

As illustrated in Figure 2.7, ultra-high-performance concrete (UHPC) mix design involves multiple key aspects, including raw material selection, packing theories, mixing procedures, and curing regimes, all of which contribute to superior performance.

Recent advances in optimization techniques, such as machine learning and genetic algorithms, have further improved mix proportioning efficiency. Machine learning models have proven effective in predicting HPC compressive strength based on material variations, reducing the need for extensive trial mixes and streamlining the design process [64].

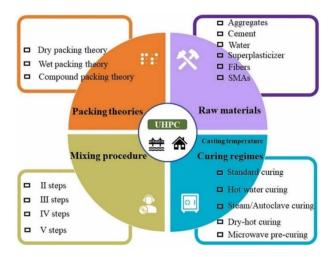


Figure 2.7: Key aspects of ultra-high-performance concrete (UHPC) mix design, including raw materials, packing theories, mixing procedures, and curing regimes [65].

2.1.3 Fresh and Hardened State Properties of HPC

2.1.3.1 Fresh State Properties and Influencing Factors

2.1.3.1.1 Key Fresh State Properties and Definitions

High-Performance Concrete (HPC) possesses several essential fresh state properties that play a pivotal role in determining its performance in construction applications. Among the most critical properties are workability, rheology, stability, and resistance to segregation. Workability refers to the ease with which concrete can be mixed, transported, placed, and finished, ensuring that the desired structural integrity and surface quality are achieved [59]. Rheology, which pertains to the material's flow and deformation characteristics, is particularly significant for HPC as it influences the ability of the concrete to flow freely under its own weight and fill complex forms without the need for mechanical vibration.

The stability of HPC is another crucial property, as it prevents segregation, where heavier components in the mix, such as aggregates, separate from the lighter cement paste. Segregation disrupts the uniformity of the concrete, compromising the material's structural performance and durability [45]. Segregation resistance, therefore, measures a concrete mix's capacity to maintain a consistent composition throughout handling and placement, which is essential for

ensuring the strength and longevity of the final structure. The incorporation of Mineral additions has been shown to significantly improve these fresh state properties, making HPC more adaptable for use in demanding civil engineering projects [40].

Table 2.5: Key fresh state properties of high-performance concrete (HPC) and their corresponding descriptions.

Property	Description	Importance
Workability	The ability of concrete to be mixed, transported, placed, and compacted easily, without issues like segregation or bleeding.	placement and
Consistency	A measure of the fluidity or flow behavior of the concrete under its own weight or external forces.	
Slump	The reduction in height of freshly mixed concrete as tested by a slump cone, reflecting its flow properties.	-
Cohesion	The capacity of the concrete mix to retain its uniform composition during mixing, transport, and placement.	•

Viscosity	The resistance of the concrete mix to	Affects pumping,
	deformation or flow under applied	spreading, and
	forces.	compacting processes,
		ensuring efficient
		handling of the mix.
Setting Time	The duration it takes for concrete to	Determines
	transition from a plastic state to a rigid	workability duration,
	or hardened condition.	scheduling for
		finishing, and
		appropriate timing for
		formwork removal.
Bleeding	The migration of excess water to the	Excessive bleeding
	surface of the concrete during settling of	weakens the concrete
	solid particles.	matrix and impacts
		bond strength and
		durability.
Segregation	The separation of coarse aggregates,	Negatively affects
	cement paste, and water due to improper	uniformity and results
	proportioning or handling.	in weaker sections or
		durability issues in the
		final structure.

2.1.3.1.2 Workability and Influencing Factors

Workability is a critical property of High-Performance Concrete (HPC), as it significantly affects its performance during mixing, transportation, and placement. It refers to the ease with which concrete can be mixed, placed, and finished, and is commonly evaluated using methods such as the slump test and flow table test. Various factors influence the workability of HPC, including the water-to-cement ratio, the type and quantity of mineral additions, and the inclusion of chemical admixtures like superplasticizers [66].

Workability is governed by multiple interdependent factors, such as aggregate particle size distribution, packing density, and rheological properties. Well-graded aggregates enhance flowability while reducing segregation, whereas rheological parameters like yield stress and plastic viscosity further define fresh concrete behavior [67]. Achieving the desired workability in HPC requires careful optimization of these factors to balance fluidity and stability.

2.1.3.1.3 Rheological Properties and Measurement

The rheological properties of High-Performance Concrete (HPC) are fundamental to understanding its behavior in the fresh state, as they significantly impact workability, pumpability, and overall performance during placement. Two key rheological parameters, yield stress and plastic viscosity, are used to describe the flow characteristics of concrete mixtures [68], [69]. Yield stress refers to the minimum force required to initiate flow, whereas plastic viscosity measures the material's resistance to flow once motion has commenced [69].

These properties are commonly assessed through rheological testing techniques, such as rotational viscometers and concrete rheometers, which provide detailed insights into how the material behaves under varying shear conditions [68], [69]. For example, concrete rheometers are particularly useful for evaluating the effects of admixtures, including superplasticizers and mineral additions, on the rheological performance of HPC [68]. Research has demonstrated that incorporating Mineral additions like silica fume can substantially influence rheological properties, leading to improvements in both workability and mix stability.

Additionally, factors such as aggregate shape, particle size distribution, and moisture content play a crucial role in determining the rheological behavior of HPC, often causing variations in yield stress and viscosity [68], [69], [70]. A thorough understanding of these interrelationships is vital for optimizing concrete formulations to achieve specific performance requirements, particularly in applications that demand high durability and strength.

It is now possible to look at relative rheology that is required in concrete for various applications and where an admixture is typically used to achieve the requirements (Figure 2.8)

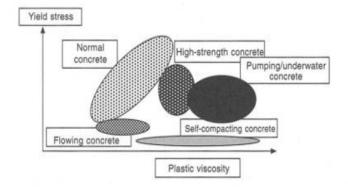


Figure 2.8: Rheological classification of concrete based on application, illustrating the relationship between yield stress and plastic viscosity for different concrete types [71].

2.1.3.1.4 Stability and Segregation Resistance

Stability in High-Performance Concrete (HPC) refers to its ability to retain a uniform composition without the separation of its components, while segregation resistance denotes the concrete's capacity to prevent the settling of heavier particles, such as coarse aggregates, during mixing and transportation [59].

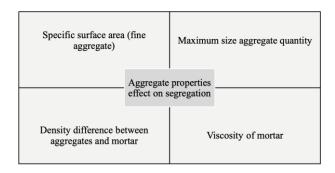


Figure 2.9: Influence of aggregate characteristics on concrete segregation [72].

Studies have shown that the addition of mineral materials such as silica fume and fly ash can enhance the stability and segregation resistance of HPC. These materials improve particle packing efficiency and reduce the water-to-cement ratio, resulting in a denser microstructure. This densification not only strengthens the mechanical properties of the concrete but also mitigates the risk of segregation [59].

2.1.3.1.5 Environmental Effects on Fresh HPC

The performance of High-Performance Concrete (HPC) in its fresh state is significantly influenced by environmental factors such as temperature, humidity, and exposure to aggressive agents. Elevated temperatures, for example, can accelerate the hydration process, which may

lead to increased thermal gradients within the concrete. These gradients can cause early-age cracking and negatively impact the workability of the material [59].

The inclusion of mineral additions, such as fly ash and silica fume, has been shown to enhance the durability of HPC under various environmental conditions. These materials contribute to the development of a refined microstructure, reducing permeability and increasing resistance to chloride ion penetration. This property is particularly advantageous in environments exposed to de-icing salts or seawater [73]. By improving both the mechanical properties and durability of HPC, these Mineral Additions play a critical role in mitigating the adverse effects of environmental stressors.

Curing conditions also play a pivotal role in determining the fresh state properties of HPC. Adequate curing ensures the retention of moisture, thereby minimizing the risks of shrinkage and cracking. On the other hand, insufficient curing, particularly in hot or windy environments, can result in rapid surface water evaporation, disrupting the hydration process and compromising the concrete's overall performance. Therefore, understanding the complex interplay between environmental factors and the properties of HPC is essential for optimizing its performance and ensuring its long-term durability in construction applications.

Table 2.6: Impact of environmental factors on the fresh state properties of high-performance concrete (HPC).

		Implications for HPC			
Environmental Factor	Impact on Fresh State Properties	Performance			
Temperature	Alters hydration rate, accelerating or	High temperatures can			
	slowing it.	lead to thermal			
		gradients, causing			
		cracking and reduced			
		workability; low			
		temperatures slow			
		down hydration.			
Humidity	Affects evaporation rates and curing	Low humidity			
	conditions.	accelerates moisture			
		loss, leading to early-			
		age cracking; high			

> humidity helps retain moisture for proper

hydration.

Speeds up surface moisture loss. Increased evaporation **Exposure to Wind**

from wind can disrupt

curing and promote

cracking.

Mineral additions(e.g., fly ash, Enhances durability and microstructure Reduces permeability

silica fume) refinement.

and improves

resistance to chloride

ion penetration,

particularly in harsh

those exposed to de-

like

environments

icing salts or seawater.

Curing Conditions Directly impacts moisture retention and Proper curing prevents

hydration process.

shrinkage and

cracking; insufficient

curing leads to rapid

evaporation and

compromised concrete

strength.

2.1.3.1.6 Summary and Implications for Fresh State Research

The investigation of fresh state properties in High-Performance Concrete (HPC) has advanced the understanding of how different Mineral additions affect its behavior. Studies emphasize the critical role of these additives in influencing properties such as workability, stability, and carbonation resistance. For example, Reiterman et al highlight that the performance of fresh concrete mixtures must be thoroughly evaluated to understand the long-term durability effects of incorporating Mineral additions such as fly ash and limestone powder [74]. Similarly, research by Singh and Singh demonstrates that the type and proportion of Mineral additions significantly impact the carbonation resistance of self-compacting concrete (SCC) mixtures.

Recent innovations in concrete technology have introduced superplasticizers and fine mineral fillers as effective solutions for enhancing the fluidity and stability of fresh HPC [75].

These findings underscore the importance of ongoing research to optimize the use of Mineral additions in HPC. Enhancing its fresh state properties not only contributes to improved performance and durability but also supports the development of more sustainable and efficient construction practices.

2.1.3.2 Hardened State Properties and Performance

2.1.3.2.1 Key Hardened State Properties and Definitions

The hardened state properties of High-Performance Concrete (HPC) are crucial for assessing its durability and overall performance. Among the key attributes are compressive strength, permeability, and resistance to environmental challenges such as freeze-thaw cycles and chemical attacks. Compressive strength, in particular, is often enhanced by the inclusion of Mineral additions such as fly ash and silica fume. These materials promote the formation of calcium silicate hydrate (C-S-H), which densifies the concrete matrix and improves its structural strength [76].

Permeability, a fundamental indicator of durability, plays a vital role in protecting concrete from the intrusion of harmful agents, thereby prolonging its service life. The incorporation of supplementary cementitious materials (SCMs) has been shown to significantly enhance concrete's resistance to aggressive environments, such as those containing sulfates and chlorides [77], [78]. These improvements are attributed to the microstructural densification achieved through the use of SCMs, which also enhances performance under cyclic loading and various environmental stressors.

The use of Mineral additions not only improves the mechanical properties of HPC but also strengthens its resilience against deterioration mechanisms. This makes HPC a reliable and durable material for challenging civil engineering applications [76], [79].

Table 2.7: Essential hardened state properties and their contribution to the durability of high-performance concrete (HPC)

Property	Description	Effect on HPC	Key Contributing	
		Durability and	Factors	
		Performance		
Compressive Strength	The concrete's capacity	Essential for structural	Enhanced by Mineral	
	to resist compressive	stability and load-	additions such as fly	
	forces without failure.	bearing ability.	ash and silica fume,	
			which aid in the	
			formation of calcium	
			silicate hydrate (C-S-	
			H).	
Permeability	The concrete's	Reducing permeability	Supplementary	
	resistance to the passage	helps prevent the entry	cementitious materials	
	of water, air, and other	of harmful substances,	(SCMs) help refine the	
	liquids.	improving longevity.	microstructure and	
			reduce permeability.	
Freeze-Thaw	The concrete's	Minimizes damage	Improved by the	
Durability	resistance to the	from freezing	incorporation of SCMs,	
	damaging effects of	conditions, preserving	which reduce pore	
	freezing and thawing	the concrete's integrity.	space and increase	
	cycles.		density.	
Chemical Resistance	The ability of concrete to	Protects the material	SCMs, including fly	
	withstand attacks from	from degradation in	ash and silica fume,	
	chemicals like sulfates	aggressive	boost resistance to	
	and chlorides.	environments,	chemical attacks, such	
		extending service life.	as sulfate and chloride	
			exposure.	
Cyclic Load Resistance	The concrete's	Increases durability	SCMs contribute to	
	performance under	under fluctuating loads,	increased toughness	
			and microstructural	

repeated loading and preventing cracking stability, enhancing unloading conditions. and fatigue failure. resistance to cyclic stresses.

2.1.3.2.2 Mechanical Properties and Performance

The mechanical properties of High-Performance Concrete (HPC) are greatly influenced by the addition of Mineral Additions, which enhance both its structural performance and durability. Essential mechanical properties, such as compressive strength, tensile strength, and modulus of elasticity, are fundamental to ensuring the structural integrity of concrete across a wide range of applications. Research has demonstrated that incorporating mineral additions, including silica fume, fly ash, and ground granulated blast furnace slag, can significantly improve these properties. For example, silica fume enhances compressive strength through its pozzolanic reaction, which facilitates the formation of additional calcium silicate hydrate (C-S-H) within the concrete matrix [66], [80].

Furthermore, the use of Mineral additions effectively reduces creep and shrinkage in concrete, which are critical for ensuring dimensional stability over time [81], [82]. Studies also highlight that pozzolanic materials, such as fly ash, not only improve mechanical strength but also increase resistance to environmental stressors, including freeze-thaw cycles and chemical degradation [59], [77], [83].

In summary, the targeted application of mineral additions in HPC enhances its mechanical properties while supporting its long-term performance and sustainability. This makes HPC a robust and reliable material for advanced civil engineering projects.

2.1.3.2.3 Durability Properties and Environmental Resistance

The durability and environmental resistance of High-Performance Concrete (HPC) are significantly improved through the integration of mineral additions. Materials such as fly ash, silica fume, and ground granulated blast furnace slag enhance HPC's ability to withstand various environmental stressors, including exposure to chloride ions, sulfates, and freeze-thaw cycles. The pozzolanic reaction between fly ash and calcium hydroxide produces additional calcium silicate hydrate (C-S-H), which densifies the concrete matrix, reduces permeability, and consequently enhances its overall durability [76], [84].

The performance of HPC in sulfate-rich environments benefits from the inclusion of these Mineral Additions, which reduce the expansion and cracking associated with sulfate attack [85], [86].

In summary, the deliberate incorporation of Mineral additions not only strengthens the mechanical properties of HPC but also significantly enhances its durability and resistance to environmental challenges. This makes HPC a highly suitable material for diverse and demanding civil engineering applications [59], [76], [77].

2.1.3.2.4 Shrinkage and Creep

The shrinkage and creep behavior of High-Performance Concrete (HPC) are critical parameters that significantly influence its long-term durability and structural performance. The incorporation of mineral additions, such as ground granulated blast furnace slag (GGBS), metakaolin (MK), and rice husk ash (RHA), has proven effective in mitigating these issues. Studies have shown that GGBS reduces both drying shrinkage and creep deformation by improving the microstructure of the concrete matrix, which leads to lower permeability and decreased moisture loss [82].

As illustrated in Figure 2.10, the evolution of deformations in HPC over a 28-day period during creep testing highlights the time-dependent nature of these effects. Metakaolin, due to its fine particle size and high reactivity, contributes to increased matrix density, reducing shrinkage-induced cracking. These improvements collectively enhance the long-term stability and durability of HPC structures.

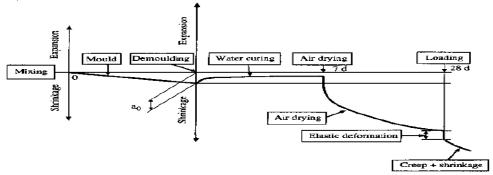


Figure 2.10: Evolution of deformations in high-performance concrete over a 28-day period during creep testing [31].

The strategic integration of Mineral additions and fibers significantly reduces shrinkage and creep in HPC while enhancing its overall performance and durability. This makes HPC a highly suitable material for demanding applications in civil engineering.

2.1.3.2.5 Microstructure and Interfacial Transition Zone

The microstructure and interfacial transition zone (ITZ) of High-Performance Concrete (HPC) are critical determinants of its mechanical performance and durability. The ITZ, located at the interface between the cement paste and aggregates, is typically more porous and less dense than the bulk cement paste, making it a potential weak point in the concrete [82]. As illustrated in Figure 2.11, the ITZ consists of key hydrate phases such as C-S-H, CH, and C-A-S-H, which influence the bonding and overall strength of the material.

The influence of the ITZ on the mechanical behavior of concrete is further demonstrated in Figure 2.12, which compares the stress-strain response of cement paste, concrete, and aggregate. This comparison highlights how the ITZ governs the overall deformation characteristics of HPC, where a well-densified ITZ leads to improved load transfer and enhanced structural integrity [87].

The use of Mineral additions has been shown to significantly enhance the microstructural characteristics of HPC by refining the pore structure and strengthening the bond between the cement matrix and aggregates. Mineral additions improve the density of the ITZ by filling voids and reducing porosity, which in turn enhances the strength and durability of the concrete. Through pozzolanic reactions, these additions generate additional calcium silicate hydrate (C-S-H) gel, which reinforces the interfacial bond and reduces the material's permeability [83]. This densification of the ITZ is a crucial factor in preventing the ingress of deleterious agents, thereby increasing the resistance of HPC to environmental degradation.

In conclusion, the incorporation of Mineral additions in HPC strategically improves the microstructure and ITZ, thereby enhancing the concrete's mechanical properties and durability. These improvements make HPC a highly reliable material for demanding civil engineering applications.

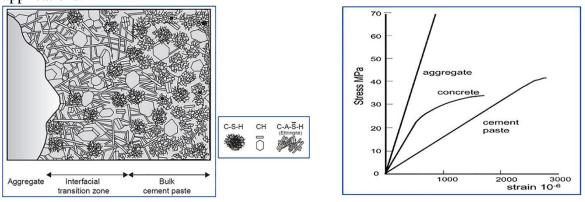


Figure 2.11: Schematic representation of the interfacial transition zone (ITZ) in concrete, illustrating the distribution of C-S-H, CH, and C-A-S-H phases [2].

Figure 2.12: Influence of the interfacial transition zone (ITZ) on the mechanical behavior of concrete, comparing the stress-strain response of cement paste, concrete, and aggregate [87].

2.1.3.2.6 Predictive Modeling and Statistical Analysis

In the realm of High-Performance Concrete (HPC), predictive modeling and statistical analysis are indispensable tools for optimizing concrete mixtures that incorporate mineral additions. These methodologies provide a framework for evaluating the relationships between critical variables, such as the type and proportion of mineral additions, and the resulting mechanical and durability properties of the concrete.

Recent research has leveraged a variety of statistical approaches, including regression analysis and machine learning techniques, to develop predictive models for assessing concrete performance. For example, Dvorkin explored the cementing efficiency of Mineral additions activated by microsilica, demonstrating how predictive models can accurately correlate the degree of hydration with the performance of low-cement concrete mixtures [88]. Similarly, Ji et al. employed numerical modeling to evaluate crack risk in early-age concrete, highlighting the significance of accounting for environmental conditions and material properties within predictive frameworks [89].

Additionally, Santos et al. conducted an analysis of the mechanical properties of concrete with partial aggregate substitution, illustrating the role of statistical techniques in identifying how variations in aggregate type influence concrete performance [90]. This approach underscores the importance of integrating experimental data with predictive modeling to enhance the reliability and precision of concrete mix designs.

Advanced modeling methodologies, such as finite element analysis and computational simulations, have further expanded the ability to predict concrete behavior under diverse loading and environmental conditions. These techniques provide valuable insights into the microstructural changes and interfacial transition zone properties that result from the inclusion of mineral additions.

In summary, predictive modeling and statistical analysis serve as powerful tools in the study of HPC with mineral additions. By facilitating the optimization of mix designs and offering a deeper understanding of material interactions, these approaches contribute to improved performance and durability, thereby supporting the advancement of civil engineering applications.

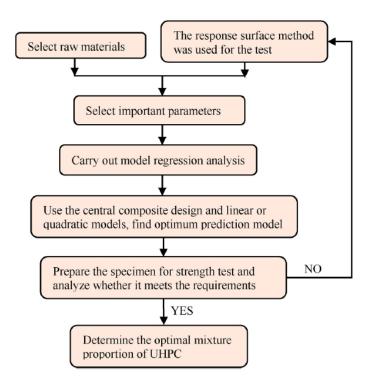


Figure 2.13: Statistical approach for optimizing the mixture design of ultra-high-performance concrete (UHPC) [91].

2.1.3.2.7 Summary and Implications for Hardened State Research

The study of the hardened state properties and performance of High-Performance Concrete (HPC) incorporating mineral additions has driven notable advancements in concrete technology. The inclusion of these Mineral additions enhances key mechanical properties, durability, and microstructural characteristics, thereby improving the overall performance of HPC in civil engineering applications.

Research has demonstrated that mineral additions significantly refine the interfacial transition zone (ITZ) between the cement paste and aggregates. This refinement reduces porosity and strengthens the bond between components, which is essential for limiting the penetration of harmful agents and improving concrete durability. Additionally, predictive modeling and statistical analysis have become indispensable tools in optimizing HPC mix designs, enabling the development of tailored solutions to meet specific performance requirements.

The investigation into the effects of different Mineral additions on HPC properties highlights the complexity of interactions within the concrete matrix. Advanced modeling methods, such

as finite element analysis, provide researchers with the ability to simulate and predict the behavior of concrete under diverse loading conditions and environmental stresses.

In conclusion, this research underscores the pivotal role of mineral additions in enhancing the hardened state properties of HPC. Continued exploration of predictive modeling and statistical techniques is expected to further propel the field, supporting the development of sustainable and high-performance concrete solutions that address the challenges of contemporary construction demands.

2.1.4 Trends in Sustainable and Innovative HPC Applications

2.1.4.1 Sustainable Construction with HPC

High-Performance Concrete (HPC) has become a cornerstone of sustainable construction practices, owing to its exceptional mechanical properties and durability, which contribute to enhanced resource efficiency and a reduction in environmental impact. The incorporation of supplementary cementitious materials (SCMs), such as fly ash and slag, not only improves the performance of HPC but also helps mitigate the carbon emissions associated with conventional cement production [92]. Additionally, integrating natural materials and recycled aggregates into concrete mixtures promotes sustainability by decreasing dependency on virgin resources and minimizing construction waste. The emergence of eco-friendly alternatives, underscores the construction industry's shift towards sustainable solutions by utilizing industrial byproducts and lowering greenhouse gas emissions.

2.1.4.2 Advances in HPC Technology and Future Directions

Recent advancements in HPC technology are centered on enhancing both its sustainability and performance through innovative materials and construction methodologies. The development of smart materials, such as self-healing concrete and 3D-printed structures, marks a transformative step in achieving more efficient and resilient construction systems [93].

As highlighted in Table 2.8, several completed 3D-printed concrete (3DPC) footbridge projects demonstrate the feasibility and structural potential of this emerging technology, paving the way for further integration into mainstream construction.

Looking ahead, future research in HPC is expected to prioritize the creation of low-carbon concrete solutions and the integration of circular economy principles. These efforts aim to ensure that construction practices align with global sustainability objectives [94].

Table 2.8: Overview of completed 3D-printed concrete (3DPC) footbridge project [93].

Project	Location	Opening Year	Lengt h (m) x Width (m)	Span (m)	Designer	Construction Company	AM Process	Typology
Footbridge "Parque de Castilla"	Alcobenda s (Spain).	2016	12.0 x 1.75	12.0	ACCIONA (ES), IAC (ES), UPC (ES)	Acciona (ES), D-Shape (IT)	D-Shape	Arch
Footbridge Gemert	Gemert (Holland)	2017	8.0 x 3.5	8.0		BAM Infra (NL), Weber Beamix (NL)	СР	Beam
Footbridge "Wisdom Bay Park"	Shanghai (China)	2019	26.3 x 3.6	14.4	Tsinghua University (CN)	Unknown	СР	Arch
Footbridge Zhaozhou	Tianjin (China)	2019	28.1 x 4.2	17.9	Hebei University of Technology (CN)	Hebei University of Technology	СР	Arch
Striatus	Venice (Italy)	2021	16.0 x 12.0	15.1	BRG (CH), ZHACODE (UK)	Incremental3D (AT), Holcim (CH)	СР	Arch
The Bridge Project	Nijmegen (Holland	2021	29.5 x 3.6	5.7	Mick Eekhout (NL), Witteveen+ Bos (NL), TU/e (NL)	BAM Infra (NL), Weber Beamix (NL)	СР	Beam
Footbridges of N243 (Holland)	N/A	N/A	12.0 x 4.5	11.0	Witteveen+ Bos (NL), TU/e (NL)	BAM Infra (NL), Weber Beamix (NL	СР	Arch

2.2 Mineral Addititions in High-Performance Concrete (HPC): Types, Properties, and Potential

2.2.1 Classification, Properties, and Key Types of Mineral Additions

2.2.1.1 Traditional Mineral additions: Fly Ash, Silica Fume, GGBFS, and Natural Pozzolans

The incorporation of traditional Mineral additions into High-Performance Concrete (HPC) has been extensively studied for their significant impact on the curing process, rheology, and durability. Among the most widely utilized additives are fly ash, ground granulated blast furnace slag (GGBS), silica fume, natural pozzolans, and limestone powder, each contributing distinct benefits to concrete performance.

2.2.1.1.1 Fly Ash

Fly ash, a byproduct of coal combustion, is highly valued for its pozzolanic properties, which enhance both the mechanical and durability characteristics of concrete. Its use can reduce the heat of hydration, improve workability, and lower the risk of cracking [95], [96]. Although high-volume fly ash mixtures may initially exhibit reduced compressive strength, studies show significant improvements in strength after extended curing periods, particularly beyond 90 days [97]. Furthermore, fly ash has been demonstrated to increase resistance to chemical attacks, such as those caused by sulfates and chlorides, thereby enhancing the overall durability of concrete [96], [98].

2.2.1.1.2 Ground Granulated Blast Furnace Slag (GGBS)

GGBS is another widely used mineral addition that enhances both the sustainability and performance of concrete. Its inclusion reduces the heat of hydration and contributes to long-term improvements in strength and durability [89]. The pozzolanic reaction of GGBS with calcium hydroxide leads to the formation of additional calcium silicate hydrate (C-S-H), which densifies the microstructure and strengthens the concrete. Research also highlights the efficacy of GGBS in mitigating damage in aggressive environments, making it an ideal choice for applications requiring enhanced durability [89].

2.2.1.1.3 Silica Fume

Silica fume, a byproduct of silicon metal production, is notable for its high pozzolanic activity and its capacity to improve the interfacial transition zone between the cement paste and aggregates [99], [100]. Its fine particle size enhances the packing density of the concrete matrix, reducing permeability and leading to significant improvements in compressive strength and

durability [101]. Additionally, silica fume has been shown to increase resistance to sulfate attack and freeze-thaw cycles, further enhancing the performance of HPC [100].

2.2.1.1.4 Natural Pozzolans

Natural pozzolans, such as volcanic ash, have been used in concrete production for centuries and are receiving renewed interest due to their environmental benefits. These materials reduce permeability and improve resistance to chemical attacks, thereby enhancing concrete durability. The pozzolanic reactions of natural pozzolans lead to the formation of additional C-S-H, which strengthens the concrete over time, similar to the effects observed with fly ash and GGBS [89]. Recent studies also underscore the sustainability potential of natural pozzolans by reducing the cement content required in concrete mixtures.

2.2.1.1.5 Limestone Powder

Limestone powder is gaining popularity as a mineral addition due to its ability to improve workability and lower water demand. Acting primarily as a filler, limestone powder enhances mechanical properties, particularly when combined with other pozzolanic materials. Additionally, it positively influences the hydration process, leading to improved strength and durability. From a sustainability perspective, the use of limestone powder helps reduce the carbon footprint of concrete production by decreasing reliance on traditional cement.

Table 2.9: Summary of Traditional Mineral additions: Classification, Characterization, and Performance Characteristics in High-Performance Concrete (HPC)

Mineral addition	eral addition Classification		Characteria	zation	Key	Performance
					Characteristics	
Fly Ash	Byproduct of	coal	Pozzolanic	material	Mitigates	heat of
	combustion.		with fine pa	article size -	hydration	, improving
			Composed	mainly of	thermal	control -
			silica, alumi	na, and iron	Enhances	workability
			oxide.		and re	educes the
					potential	for cracking -
					Promotes	long-term
					strength	development,
					especially	after 90 days

> - Improves durability by increasing resistance to chemical attacks, such as sulfates and chlorides.

> > heat

Granulated Byproduct of the blast Pozzolanic and latent Reduces Ground **Blast** Slag furnace steel production hydraulic properties - generation during early **Furnace** (GGBS) Rich in process. silica and alumina.

Silica Fume

amorphous hydration stages Contributes to long-

strength term enhancement through

> C-S-H additional

> formation - Enhances

resistance to

environmental

degradation,

particularly in aggressive settings

(e.g., sulfate attack,

the

transition

chloride-induced

corrosion).

Byproduct of silicon Highly reactive Strengthens metal production. amorphous silica with a interfacial

> very fine particle size. zone between cement

paste and aggregates -

Reduces permeability,

significantly improving

compressive strength

durability and Bolsters resistance to

sulfate attack and

freeze-thaw damage -

Enhances the packing

37

> density of the concrete matrix, improving mechanical properties.

> > improving

Natural Pozzolans

occurring Enhances durability by Volcanic ash, pumice, Naturally material reducing permeability diatomite. pozzolanic with high silica and and

alumina content.

chemical resistance -Promotes the formation of additional calcium silicate hydrate (C-S-H), leading to progressive strength gain - Contributes to the reduction of cement content, promoting sustainability in concrete production.

Limestone Powder

inert Improves workability Filler material derived Predominantly with limited pozzolanic and from natural limestone. reactivity.

reduces water demand - Enhances the mechanical properties of concrete, particularly when combined with other pozzolanic materials - Contributes to reducing the carbon footprint by substituting part of the in content cement mixtures.

2.2.1.2 Emerging and Advanced Mineral Additions

The utilization of emerging and multi-scale Mineral additions in High-Performance Concrete (HPC) has garnered significant attention in recent years. This section examines recent advancements in the application of calcined clays, metakaolin, nano-silica, recycled and wastebased additives, and other innovative materials. These additives not only improve the performance characteristics of HPC but also contribute to sustainability in the construction industry.

2.2.1.2.1 Calcined Clays and Metakaolin

Calcined clays, particularly metakaolin, are increasingly recognized as effective supplementary cementitious materials (SCMs) due to their superior pozzolanic properties. Metakaolin, produced through the calcination of kaolinite clay at temperatures ranging from 600°C to 800°C, is highly reactive and significantly enhances the mechanical and durability properties of HPC. Research has shown that the inclusion of metakaolin improves compressive strength, reduces permeability, and enhances resistance to aggressive environments. The pozzolanic reaction between metakaolin and calcium hydroxide generates additional calcium silicate hydrate (C-S-H), which densifies the concrete matrix. Furthermore, metakaolin is effective in mitigating the heat of hydration, making it particularly suitable for mass concrete applications.

2.2.1.2.2 Nano-Silica

Nano-silica is an innovative additive that has demonstrated considerable potential in enhancing the properties of HPC. Its ultra-fine particle size enables it to fill voids within the concrete matrix, resulting in improved packing density and reduced permeability. Studies indicate that the addition of nano-silica enhances both compressive and flexural strength, particularly at early curing stages. Moreover, nano-silica contributes to the development of a denser microstructure, which improves resistance to chemical attacks and environmental degradation. Recent findings also highlight its ability to improve the rheological properties of fresh concrete, thereby enhancing workability without compromising strength [102].

2.2.1.2.3 Recycled and Waste-Based Additives

The incorporation of recycled and waste-based additives into concrete production offers an innovative solution to environmental challenges while improving material performance. Recycled concrete aggregates (RCA), derived from construction and demolition waste, have been widely studied as a replacement for natural aggregates. Research demonstrates that RCA, when properly processed and combined with suitable SCMs, can achieve mechanical properties comparable to conventional concrete. Additionally, recycled materials such as glass powder

and plastic waste enhance the sustainability profile of HPC while providing specific performance benefits. For instance, recycled glass powder improves resistance to alkali-silica reaction (ASR) and enhances the durability of concrete [103].

2.2.1.3 Other Emerging Mineral Additions

Beyond these widely studied additives, other innovative materials are being explored for their potential in HPC applications. Rice husk ash (RHA), for instance, has emerged as a sustainable pozzolanic material that enhances the strength and durability of concrete while reducing the carbon footprint associated with cement production. Similarly, marine biorefinery waste has been proposed as a mineral addition, offering a dual benefit of reducing land pollution and contributing to the environmental sustainability of concrete. These novel materials not only improve the mechanical properties of HPC but also align with global efforts to promote sustainable construction practices.

The integration of emerging and multi-scale mineral additions, including calcined clays, nanosilica, recycled materials, and other innovative solutions, represents a significant opportunity for enhancing the performance and sustainability of HPC. Ongoing research and development in this domain are vital for advancing concrete technology and addressing the limitations of conventional construction practices.

2.2.2 Key Properties and Behavior of Selected Mineral additions

2.2.2.1 Andesite: Composition, Workability, and Strength

Andesite, a volcanic rock, has gained prominence as a mineral addition in High-Performance Concrete (HPC) due to its distinctive composition and advantageous properties. Its mineralogical composition, predominantly consisting of plagioclase, pyroxene, and volcanic glass, contributes to its ability to enhance the mechanical strength and durability of concrete when incorporated into mixtures [104]. The use of andesite as a fine mineral addition also improves the workability of concrete, an essential attribute for high-performance applications that require superior fluidity and ease of placement [105].

Research has demonstrated that andesite powder significantly influences the rheological behavior of concrete. Studies indicate that incorporating andesite into concrete formulations enhances flowability, thereby reducing the water-to-cement ratio required to achieve desired workability levels [104]. This property is particularly valuable in HPC, where maintaining low porosity and achieving high density are critical for optimizing mechanical performance and durability [106]. Additionally, the pozzolanic activity of andesite facilitates the formation of

supplementary calcium silicate hydrate (C-S-H) during the hydration process, further improving compressive strength.

Experimental investigations have confirmed that concrete incorporating andesite outperforms conventional mixtures in terms of compressive strength. For example, studies utilizing waste andesite powder revealed that increasing the proportion of andesite enhanced compressive strength, with optimal results observed at specific replacement levels [104]. This improvement is attributed to the effective filling of voids within the concrete matrix and the strengthening of the interfacial transition zone (ITZ) between aggregates and cement paste. Moreover, the mechanical resilience of andesite-enhanced concrete under adverse environmental conditions makes it highly suitable for use in aggressive settings.

Andesite from the Tipaza region of Algeria has garnered considerable research interest due to its promising pozzolanic properties, which make it an effective supplementary cementitious material (SCM). A detailed study conducted by Hamidi et al assessed the pozzolanic activity of andesite and established its suitability as a partial replacement for Portland cement in concrete mixtures [107]. The findings revealed that andesite exhibits moderate pozzolanic activity, surpassing that of several natural pozzolans, thereby positioning it as a valuable resource for eco-efficient cement production [108]. The incorporation of andesite into concrete formulations has demonstrated notable enhancements in compressive strength and durability, underscoring its potential for diverse construction applications in Algeria [107].

In addition, ongoing research conducted continues to focus on optimizing the utilization of andesite in concrete production. These studies emphasize its capacity to contribute to sustainable construction practices by reducing the environmental impact of cement manufacturing and addressing the increasing demand for environmentally friendly materials in the construction industry [109]. The promising results highlight the potential of andesite as a key component in advancing Algeria's sustainable construction initiatives.

In conclusion, andesite's distinct composition and pozzolanic properties position it as a valuable mineral addition for high-performance concrete. Its ability to improve workability, increase compressive strength, and potentially reduce drying shrinkage underscores its suitability for modern concrete applications, particularly in environments requiring exceptional durability and performance.

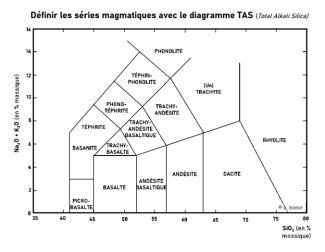


Figure 2.14: TAS (Total Alkali-Silica) diagram for the chemical classification of volcanic rocks [110].

2.2.2.2 Calcined Marl: Hydraulic Activity and Durability

Calcined marl has gained attention as an effective supplementary cementitious material (SCM) due to its hydraulic properties and its ability to enhance the durability of concrete. The calcination process activates marl, which is primarily composed of clay minerals and calcium carbonate, transforming it into a reactive pozzolanic material capable of improving the mechanical performance of concrete. Recent investigations have demonstrated that incorporating calcined marl into concrete mixtures significantly enhances compressive strength and durability, particularly under harsh environmental conditions [11]. For example, concrete containing calcined marl has shown increased resistance to chloride ion penetration, a critical property for structures exposed to de-icing salts and marine environments [11].

As shown in Figure 2.15, marls can be classified based on their carbonate and clay content, which directly influences their reactivity and suitability as SCMs. Furthermore, as illustrated in Figure 2.16, the CaO–SiO₂–Al₂O₃ ternary diagram provides a comparative analysis of the chemical composition of various marls reported in the literature, emphasizing their variability and impact on cementitious behavior.

The durability of concrete incorporating calcined marl has been further supported by experimental studies. Benkabouche's research on mortars containing calcined river sediments, a material with similar characteristics, revealed satisfactory performance in sulfate-rich environments, suggesting comparable benefits for calcined marl [111]. Additionally, studies have emphasized the effectiveness of calcined materials in mitigating sulfate attack, thereby extending the service life of concrete structures [112]. The pozzolanic reaction of calcined marl

promotes the formation of additional calcium silicate hydrate (C-S-H), which densifies the microstructure and reduces porosity, resulting in enhanced durability.

The environmental advantages of calcined marl further underscore its value as an SCM. Its lower calcination temperature compared to traditional cement manufacturing reduces carbon dioxide emissions, making it a more sustainable option for concrete production. By improving the performance of concrete while reducing environmental impact, calcined marl aligns with the increasing demand for sustainable materials in the construction industry.

In summary, calcined marl demonstrates considerable potential as a mineral addition in concrete. Its hydraulic activity, durability-enhancing properties, and eco-friendly benefits make it a valuable resource for high-performance concrete applications, particularly in settings requiring long-term resistance to aggressive environments.

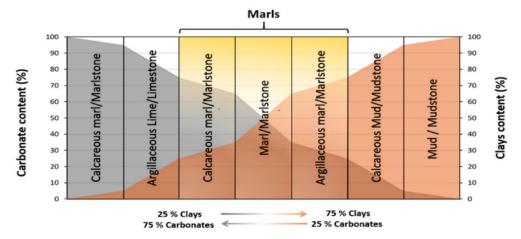


Figure 2.15: Classification of marls based on carbonate and clay content [11].

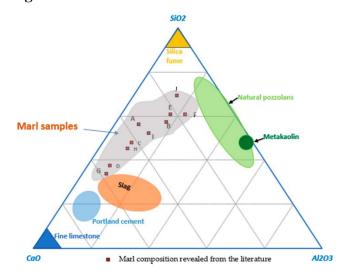


Figure 2.16: CaO–SiO₂–Al₂O₃ ternary diagram illustrating the chemical composition of various marls reported in the literature: (A) [113], (B) [114], (C) [115], (D) [116], (E) [117], (F) [118], (G) [119], (H) [120], (I) [121], (J) [122]. [11]

2.2.2.3 Natural Pozzolan: Pozzolanic Mechanisms and Strength Development

Natural pozzolans, particularly those sourced from Algeria, are increasingly recognized for their capacity to improve the mechanical properties and durability of concrete through pozzolanic reactions. In Algeria, notable deposits of natural pozzolans are concentrated in the western region, especially around Beni-Saf, where volcanic activity has resulted in the formation of high-quality pozzolanic materials [123]. These materials are distinguished by their high silica and alumina content, which react with calcium hydroxide (Ca(OH)₂) released during the hydration process of Portland cement. This reaction generates additional calcium silicate hydrates (C-S-H), which contribute to a denser and stronger concrete matrix.

Recent research has highlighted the significant benefits of incorporating natural pozzolans into concrete mixtures, particularly in terms of compressive strength and durability. Studies reveal that concrete containing natural pozzolans demonstrates enhanced resistance to sulfate attack and reduced permeability, making it an ideal choice for structures in aggressive environmental conditions [124]. Furthermore, the gradual strength development associated with pozzolanic reactions enables a continued improvement in mechanical properties over time, which is especially advantageous for infrastructure requiring long-term durability.

The environmental advantages of utilizing natural pozzolans are also noteworthy. Their integration into concrete reduces the dependency on Portland cement, thereby lowering the carbon emissions associated with its production. This contribution aligns with global sustainability initiatives and supports the growing demand for environmentally friendly construction materials.

In conclusion, natural pozzolans play an essential role in enhancing pozzolanic activity and promoting the strength development of concrete. Their distinct chemical composition and local availability in Algeria make them a valuable addition to high-performance concrete, contributing to both technical performance and environmental sustainability.

2.2.3 Cement-Additive Interaction Mechanisms and Effects on Concrete Properties

2.2.3.1 Pozzolanic Reactions

The pozzolanic reactions associated with andesite, calcined marl, and natural pozzolan are integral to improving the performance of concrete. Algerian andesite, in particular, has exhibited noteworthy pozzolanic activity. As highlighted by Hamidi et al, the silica and alumina content in andesite reacts effectively with calcium hydroxide during the hydration process [107]. This reaction leads to the formation of additional cementitious compounds, such as

calcium silicate hydrates (C-S-H), which significantly enhance the mechanical strength of concrete. These findings underscore the potential of andesite as a sustainable alternative to conventional cementitious materials.

Calcined marl, when subjected to thermal activation, also demonstrates enhanced pozzolanic properties. Studies reveal that calcining marl at temperatures ranging from 600 to 800 °C markedly increases its reactivity, enabling it to bind with calcium hydroxide and contribute to the generation of C-S-H. This transformation improves the mechanical performance of concrete while presenting a sustainable option for reducing reliance on traditional cement-based materials.

In the Beni-Saf region of Algeria, natural pozzolan is a widely available resource that has been effectively utilized in cement production. Research indicates that integrating natural pozzolan from this area into concrete improves its durability and resistance to sulfate attacks, making it highly suitable for use in aggressive environments. Typically incorporated as a partial replacement for cement at rates of 15-20%, this local pozzolan not only enhances mechanical properties but also reduces the environmental impact of concrete production, aligning with sustainable construction practices.

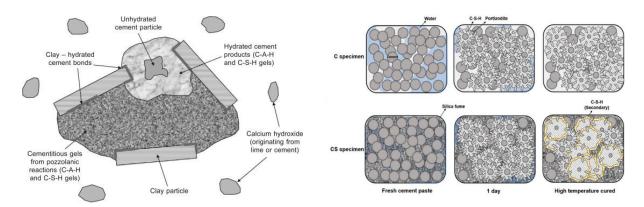


Figure 2.17: Formation of cementitious bonding products during hydration and long-term pozzolanic reactions, highlighting C-A-H and C-S-H gels [125].

Figure 2.18: Schematic representation of cement hydration and pozzolanic reactions in specimens with a low water-to-cement (w/c) ratio, illustrating microstructural evolution over time and under high-temperature curing [126].

2.2.3.2 Microstructural Interactions

Microstructural interactions between cement and Mineral additions such as andesite, natural pozzolan, and calcined marl are critical for enhancing the performance of High-Performance Concrete (HPC). The addition of these materials refines the pore structure within the concrete matrix by reducing both pore size and connectivity. This densification is essential for enhancing durability, as it minimizes the pathways through which moisture and aggressive ions can infiltrate the concrete. Scanning Electron Microscopy (SEM) analyses have revealed that pozzolanic reactions facilitate the formation of additional calcium silicate hydrates (C-S-H), which effectively fill voids and improve the bond between the cement paste and aggregates.

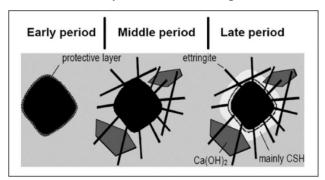


Figure 2.19: Microstructural evolution of cement hydration over time [127].

In conclusion, the microstructural interactions enabled by Mineral additions are integral to defining the properties of high-performance concrete. The densification of the concrete matrix through pozzolanic reactions, coupled with enhanced bonding at the interfacial transition zone (ITZ), significantly improves both durability and mechanical performance. As illustrated in Figure 2.20, ultrafine particles act as fillers in superplasticized cement paste, further refining the microstructure by reducing porosity and enhancing packing density.

This is particularly relevant in the Algerian context, where leveraging local materials offers both economic and sustainability benefits.

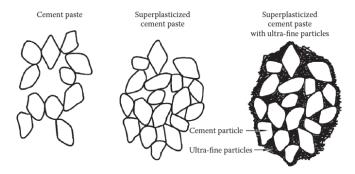


Figure 2.20: Ultrafine particles acting as fillers in superplasticized cement paste [128].

2.2.4 Effects of Mineral additions on Fresh and Hardened Concrete Properties

2.2.4.1 Workability and Rheological Behavior

The inclusion of Mineral additions plays a pivotal role in shaping the workability and rheological characteristics of concrete, which are critical parameters for achieving optimal performance in high-performance concrete (HPC). Traditional supplementary cementitious materials (SCMs), such as fly ash, silica fume, and slag, have been the subject of extensive research. Fly ash, for example, is recognized for its ability to improve workability due to its spherical particle morphology, which facilitates a "ball-bearing effect" that enhances interparticle movement within the concrete matrix [129]. However, when used in excessive quantities, fly ash may lead to reduced workability as a result of increased water demand [130].

As illustrated in Figure 2.21, the specific surface area of mixed oxides derived from layered double hydroxides influences both the rheology and porosity of cement paste, demonstrating the interplay between fine particle interactions and flow behavior. Meanwhile, silica fume, despite its contribution to strength and durability, tends to reduce workability due to its ultrafine particle size, necessitating the use of superplasticizers to maintain adequate fluidity [131].

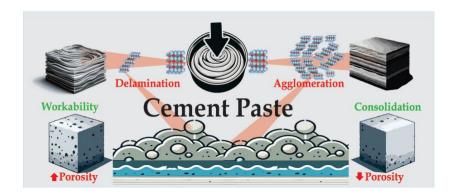


Figure 2.21: Influence of mixed oxide specific surface from layered double hydroxides on the rheology and porosity of cement paste [132].

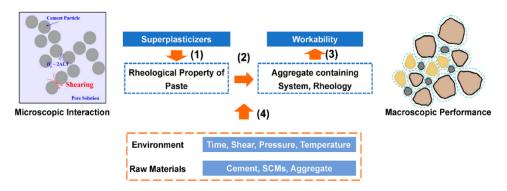


Figure 2.22: Key factors influencing the effect of chemical admixtures on concrete workability [47].

Mineral additions such as andesite, calcined marl, and natural pozzolan have demonstrated considerable potential in improving the workability and rheological properties of concrete. Andesite, for example, has been reported to enhance both compressive strength and workability. This improvement is attributed to its fine particle size and unique mineralogical composition, which contribute to increased packing density and a reduction in water demand [104].

Calcined marl has shown the ability to maintain workability while simultaneously enhancing the mechanical properties of concrete. Its pozzolanic activity aids in reducing the water-cement ratio, resulting in improved rheological performance without compromising the fluidity of the mixture. Similarly, natural pozzolans have been extensively investigated for their positive impact on rheological behavior. These materials enhance the cohesiveness of concrete, reducing segregation and ensuring uniformity, which is critical for achieving high strength and durability.

In conclusion, the deliberate integration of these Mineral additions provides a pathway to optimize workability and rheological characteristics, making them indispensable for the development of advanced HPC formulations tailored to meet modern construction demands.

2.2.4.2 Segregation Resistance

The segregation resistance of concrete is a crucial attribute that ensures uniformity and stability in both its fresh and hardened states. The incorporation of various Mineral additions has been shown to have a significant impact on this property. Andesite, a volcanic rock, enhances segregation resistance through its angular particle shape and high surface area. These characteristics promote better particle interlocking, thereby reducing the likelihood of separation during mixing and placement.

Because of their fineness, silica fume particles can fill the voids between the larger cement particles, when they are well deflocculated in the presence of an adequate dosage of superplasticizer, as shown in Figure 2.23. The filler effect is also said to be responsible for the increase in fluidity of concretes with a very low water/binder ratio. Therefore, owing to its unique physical characteristics, the resulting solid matrix including silica fume is dense even before any chemical bonds between the cement particles have developed.

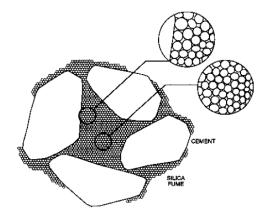


Figure 2.23: Microstructural illustration of the filler effect of silica fume in cementitious systems [133].

Similarly, calcined marl has demonstrated a positive influence on segregation resistance by improving the cohesiveness of concrete mixtures. Its pozzolanic activity contributes to the development of a denser microstructure, effectively minimizing issues such as bleeding and segregation [134]. Natural pozzolans also enhance the stability of concrete mixtures by improving the binding capacity of the paste, reducing the potential for segregation during handling and placement.

Furthermore, the combined use of superplasticizers with these Mineral additions can significantly enhance segregation resistance by optimizing the rheological properties of concrete.

In conclusion, the deliberate incorporation of Mineral additions such as andesite, calcined marl, and natural pozzolan, combined with the judicious use of chemical admixtures, can substantially improve the segregation resistance of concrete. This enhancement makes concrete more suitable for high-performance applications, ensuring durability and uniformity in demanding construction environments

2.2.4.3 Water Demand and Plastic Shrinkage

The effect of Mineral additions on water demand and plastic shrinkage in high-performance concrete (HPC) is a vital research area due to its implications for the sustainability and long-term durability of concrete structures. Additives such as calcined clays and calcined marl have been shown to have a profound influence on these properties.

Calcined clays, particularly metakaolin, are recognized for their significant pozzolanic activity, which enhances the water retention capacity of concrete. The fine particle size and high specific

surface area of metakaolin improve the cohesion within the concrete matrix, leading to a reduction in water demand and mitigation of plastic shrinkage [135]. Studies suggest that using metakaolin at an optimal dosage can effectively lower water demand while preserving workability, a critical factor for ensuring the desired performance in HPC [136].

Similarly, calcined marl has been identified as a highly effective pozzolan that not only enhances the mechanical properties of concrete but also reduces water demand. The inclusion of calcined marl improves the concrete's microstructure, reducing permeability and plastic shrinkage [137], [138]. Research demonstrates that calcined marl can significantly minimize the negative effects of plastic shrinkage, thus preserving the structural integrity of concrete during the curing phase.

As illustrated in Figure 2.24, the water/cement ratio and hydration degree play a crucial role in defining the permeability and compressive strength of concrete, further highlighting the necessity of optimizing water demand for improved durability.

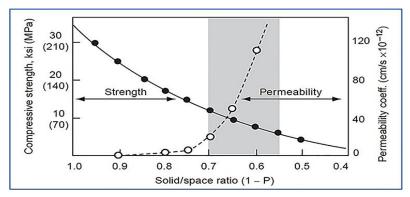


Figure 2.24: Effect of water/cement ratio and hydration degree on the permeability and compressive strength of concrete [2].

2.2.4.4 Mechanical Strength and Durability

The incorporation of mineral additions, including andesite, calcined marl, and other pozzolanic materials, plays a pivotal role in improving the mechanical strength and durability of high-performance concrete (HPC). Andesite, a volcanic rock, has been found to enhance the compressive strength of concrete due to its advantageous mineralogical composition and particle morphology. Research indicates that well-graded and appropriately treated andesite aggregates contribute to superior mechanical properties in concrete [104]. Additionally, the pozzolanic activity of andesite waste powder has been well-documented, demonstrating its effectiveness as a partial cement replacement for increasing concrete strength [9].

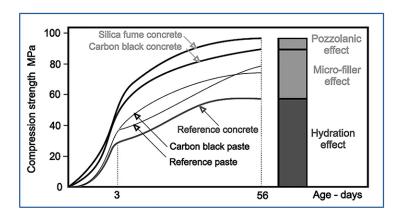


Figure 2.25: Hydration, pozzolanic, and micro-filler effects in cementitious pastes incorporating silica fume [139].

Calcined marl is another highly effective mineral addition that significantly enhances the mechanical performance and durability of HPC. Its pozzolanic activity refines the microstructure of the concrete, resulting in higher density and lower permeability—attributes essential for improving resistance to environmental challenges. Studies have linked the inclusion of calcined marl to enhanced protection against chloride ingress and reduced vulnerability to alkali-silica reactions (ASR), both of which are critical for extending the lifespan of concrete structures [140].

2.2.5 Multi-Scale Effects on Rheology and Hardened Properties

Mineral additions exert significant multi-scale effects on both the rheological behavior of fresh concrete and the hardened properties of the material. At the micro-scale, these additives alter the hydration kinetics of cement, leading to complex interactions between the binder and aggregates [66]. Such interactions improve the flow characteristics of fresh concrete, as evidenced by studies exploring the use of various Mineral Additions [141]. On the macro-scale, the inclusion of fly ash and slag has been found to enhance the long-term strength and durability of hardened concrete, particularly under aggressive environmental conditions. Moreover, these additives synergistically improve resistance to environmental stressors, including freeze-thaw cycles and chloride-induced corrosion, further enhancing the material's longevity [59].

2.2.6 Sustainability, Carbon Reduction, and Lifecycle Impact

2.2.6.1 Reduction of Cement Content and CO₂ Emissions

A primary approach to reducing CO₂ emissions in concrete production involves partially substituting Portland cement with supplementary cementitious materials (SCMs) such as fly

ash, slag, and metakaolin. These materials not only decrease the reliance on traditional cement but also enhance the mechanical performance and longevity of concrete. For instance, research indicates that replacing up to 30% of cement with fly ash can substantially lower the carbon footprint of concrete while maintaining or even improving its compressive strength. Additionally, SCMs contribute to a reduction in the heat of hydration, making them particularly advantageous for large-scale concrete applications where thermal cracking poses a challenge [59].

Lifecycle assessment (LCA) studies of concrete containing SCMs further highlight its environmental benefits, showing significant reductions in greenhouse gas emissions compared to conventional concrete. High-performance concrete incorporating recycled materials demonstrates particularly low environmental impact, particularly in terms of CO₂ emissions from cement production [142]. This transition towards more sustainable concrete formulations aligns with global efforts to mitigate climate change and foster eco-friendly construction practices.

2.2.6.2 Impact on Lifecycle Performance and Carbon Footprint

The lifecycle performance of concrete is significantly influenced by its composition, particularly the use of Mineral additions. High-performance concrete containing these materials generally demonstrates improved durability, extending the lifespan of structures and minimizing the need for frequent repairs and replacements. This durability reduces lifecycle costs and environmental impacts over the service life of concrete.

Additionally, the carbon footprint of concrete can be significantly reduced through lifecycle assessment (LCA) methodologies, which evaluate environmental impacts across all stages of a concrete structure's life—from raw material extraction to end-of-life disposal. Research findings indicate that high-performance concrete incorporating SCMs achieves notable reductions in lifecycle emissions compared to traditional concrete formulations. By optimizing mix designs and adopting sustainable materials, the construction industry can effectively decrease both carbon emissions and resource consumption.

The integration of Mineral additions in high-performance concrete supports substantial reductions in cement content and associated CO₂ emissions. Furthermore, the valorization of industrial byproducts and waste materials enhances the sustainability of concrete formulations. These practices not only improve lifecycle performance but also align with global objectives for reducing carbon footprints in the construction industry. By adopting such strategies, the

sector can advance toward more sustainable and environmentally responsible building solutions.

2.3 Activation of Pozzolanic Properties in Mineral additions: Calcination and Reactivity Assessment

2.3.1 Pozzolanic Activity: Mechanisms, Activation, and Assessment Methods

2.3.1.1 Definition, Importance, and Activation Techniques in HPC

Pozzolanic materials are defined as siliceous or siliceous-aluminous substances that, in the presence of moisture, react chemically with calcium hydroxide (Ca(OH)₂) at ambient temperature to form cementitious compounds. The integration of pozzolans in high-performance concrete (HPC) plays a pivotal role in enhancing its mechanical strength, durability, and environmental sustainability by reducing reliance on ordinary Portland cement, which has a high carbon footprint [124]. Various activation techniques, including thermal, chemical, and mechanical methods, are employed to enhance the reactivity and performance of pozzolanic materials in cementitious systems.

Thermal activation involves heating pozzolanic materials to specific temperatures to increase their reactivity. For instance, calcining kaolinite at approximately 700–800 °C produces metakaolin, a material with significantly enhanced pozzolanic properties due to its altered mineralogical structure [143]. Chemical activation typically involves the use of alkaline solutions, such as sodium hydroxide (NaOH) or sodium silicate (Na₂SiO₃), to improve the dissolution of silica and alumina, thereby accelerating pozzolanic reactions.

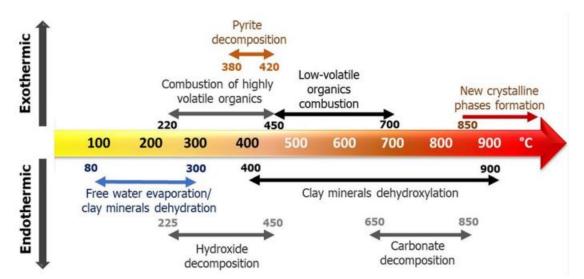


Figure 2.26: Temperature ranges of key reactions occurring during the calcination of clays [144].

2.3.1.2 Chemical, Physical, and Thermal Activation Mechanisms

The mechanisms governing pozzolanic activity can be categorized into chemical, physical, and thermal processes. Chemically, pozzolans react with calcium hydroxide released during the hydration of Portland cement, forming additional calcium silicate hydrate (C-S-H) and other cementitious compounds that improve the strength and durability of concrete. This reaction is most effective when pozzolans possess a high content of reactive silica and alumina.

From a physical perspective, the activation of pozzolans enhances their particle size distribution and surface area, which leads to better packing density and reduced porosity in concrete. Thermal activation, as mentioned previously, involves subjecting pozzolanic materials to heat, which alters their mineralogical composition and increases their reactivity. Research indicates that thermal treatment significantly enhances the pozzolanic activity of materials such as metakaolin and volcanic ash, yielding superior performance in concrete applications [143].

Table 2.10: Techniques for enhancing pozzolanic activity.

Technique	Description	Advantages	Challenges
Thermal Activation	Subjecting raw	Enhances pozzolanic	Energy-intensive
(Calcination)	materials, such as clay or		process.
	temperatures to remove	transforming crystalline phases into amorphous, reactive forms. - Suitable for various natural resources.	- May result in CO ₂ emissions during production.
Mechanical Activation	•	Promotes faster reactions due to increased surface area Economical for certain applications.	

Chemical Activation	Introducing chemical activators such as sodium hydroxide (NaOH), sodium sulfate (Na ₂ SO ₄), or calcium chloride (CaCl ₂) to accelerate pozzolanic reactions.	Enhances early-age reactivity. - Optimizes performance under specific conditions.	Potential for incompatibility with other mix components. - Additional costs involved.
Hydration Management	Optimizing the water-to- binder ratio to facilitate effective interaction between pozzolanic materials and cementitious compounds	•	Requires meticulous mix design control to balance hydration
Blending with Portland Cement	Incorporating pozzolans into cement to utilize calcium hydroxide (Ca(OH) ₂) produced during hydration for secondary reactions.	•	May slow early-age strength development, requiring careful proportioning.
High-Temperature Curing	Exposing concrete to elevated temperatures, such as steam curing, to accelerate pozzolanic and hydration reactions.	Speeds up setting and strength development. - Beneficial for prefabrication processes.	Requires precise temperature control to avoid thermal cracking and shrinkage.
Use of Superplasticizers	Improving the dispersion and distribution of pozzolanic particles within the concrete matrix to enhance reactivity.	Ensures uniform particle dispersion. - Improves workability and reduces porosity.	Requires compatibility assessments with other admixtures.

Combination	Integrating	multiple	e Optimizes performance	May	increase
Techniques	methods,	such a	s through	complexity	and
	mechanical	and	l complementary	production cos	ts.
	chemical ac	ctivation, to	mechanisms.		
	achieve synergistic		- Adaptable to diverse		
	improvemen	nts in	applications.		
	pozzolanic a	ectivity.	upp nouvious.		

2.3.1.3 Indicators and General Methods for Assessing Pozzolanic Activity

Evaluating the pozzolanic activity of materials is crucial for determining their suitability as supplementary cementitious materials. Commonly used methods include the Frattini test, the saturated lime method, and the Chapelle method.

The Frattini test measures the reactivity of pozzolans by quantifying the calcium hydroxide consumed in a saturated lime solution over time, with higher consumption indicating greater pozzolanic activity [145]. The saturated lime method involves mixing pozzolans with a lime solution and monitoring the strength gain over time, offering valuable insights into their long-term performance in cementitious systems [146].

The Chapelle method calculates the amount of lime consumed during the pozzolanic reaction, providing a direct measurement of reactivity. This technique is widely adopted in research due to its reliability [147]. Additional methods, such as the strength activity index (SAI), compare the compressive strength of mortars containing pozzolans to control samples without pozzolans to assess performance [145]. Advanced techniques, including thermogravimetric analysis (TGA) and X-ray diffraction (XRD), are also employed to analyze the mineralogical changes and hydration products formed during pozzolanic reactions [148].

Despite these established assessment methods, gaps remain in understanding the long-term durability and performance of various pozzolanic materials under specific environmental conditions. Further research is required to standardize testing protocols and enhance the understanding of interactions between pozzolans and cementitious systems.

2.3.2 Microstructural and Analytical Techniques for Characterizing Reactivity

2.3.2.1 Microstructural Techniques and Mineralogical Analysis (SEM, XRD, EDX)

The characterization of concrete microstructure is essential for assessing its performance, particularly when Mineral additions are included. Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), and Energy Dispersive X-ray Spectroscopy (EDX) are critical tools used to investigate the microstructural and mineralogical attributes of concrete. SEM provides high-resolution imaging, enabling the detailed examination of the morphology and spatial distribution of hydration products such as calcium silicate hydrate (C-S-H) and the interfacial transition zone (ITZ) between aggregates and cement paste. Recent studies indicate that incorporating pozzolanic materials can result in a denser microstructure, which enhances both mechanical strength and durability.

XRD complements SEM by identifying and quantifying the crystalline phases within the concrete, which is crucial for understanding the hydration reactions during curing. The detection of phases such as ettringite and C-S-H provides insights into the material's performance characteristics [149]. EDX, often integrated with SEM, facilitates the elemental analysis of observed phases, enabling the evaluation of the chemical composition and the effectiveness of Mineral additions in promoting pozzolanic activity and overall reactivity [150].

2.3.2.2 Key Factors Influencing Reactivity: Physical and Chemical Properties

The reactivity of Mineral additions in concrete depends on their physical and chemical attributes, including particle size, surface area, and composition. Smaller particles with higher surface areas enhance pozzolanic reactions by providing more reactive sites for interactions with calcium hydroxide (Ca(OH)₂). For example, nanosilica significantly improves the mechanical performance of concrete due to its extensive surface area, which facilitates the formation of additional C-S-H gel [151].

Chemical composition, particularly the silica-to-alumina ratio, is another critical determinant of pozzolanic activity. Materials with high silica content, such as silica fume and fly ash, exhibit superior reactivity compared to those with lower silica levels [152]. Furthermore, the use of alkaline activators can enhance the dissolution of silica and alumina, thereby accelerating the pozzolanic reactions and improving the material's overall performance.

Environmental factors, such as curing conditions, also significantly influence the reactivity of mineral additions. Temperature and humidity impact the hydration kinetics and the development of the microstructure, which directly affects the concrete's mechanical properties

[83]. However, there is a lack of comprehensive investigations into the combined effects of these factors on the reactivity and performance of various Mineral additions in concrete.

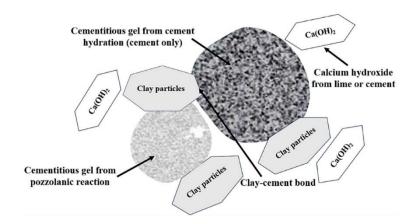


Figure 2.27: Schematic representation of strength development through pozzolanic reaction products [153].

2.3.3 Summary of Findings, Research Gaps, and Future Directions

2.3.3.1 Key Findings, Limitations, and Gaps in Reactivity Assessment

The enhancement of pozzolanic properties in Mineral additions via calcination has been the subject of extensive research, highlighting several critical factors. The reactivity of pozzolanic materials is significantly affected by the type of clay minerals, the presence of impurities, and the specific parameters of thermal activation, such as temperature and duration. Optimal calcination temperatures, often around 900°C, have been identified for certain clays. Exceeding these temperatures can lead to the formation of inert crystalline phases, which diminish reactivity [154]. Additionally, the reactivity of calcined materials is closely tied to the development of an amorphous phase and the particle size achieved during calcination, with finer particles and higher surface areas exhibiting superior pozzolanic performance [154], [155].

Despite these advancements, challenges and knowledge gaps persist in the evaluation of pozzolanic reactivity. Much of the existing research is concentrated on widely studied mineral types, leaving limited understanding of less common pozzolanic materials. Moreover, the lack of standardized methodologies for assessing reactivity introduces inconsistencies in results and interpretations across studies [156]. Addressing these issues requires the development of uniform testing protocols, which would enable more reliable comparisons of different pozzolanic materials and their calcination processes [156].

2.4 Thermal Curing and Heat Treatment in Concrete

2.4.1 Overview, Objectives, and Mechanisms of Thermal Curing

2.4.1.1 Definition, Importance, and Historical Context

Thermal curing, commonly referred to as heat treatment, is a process in which concrete is exposed to elevated temperatures during its initial hydration phase to expedite strength development and achieve other beneficial properties [157]. This method has been extensively adopted in the precast concrete industry to attain high early-age strength and facilitate rapid production cycles [158]. The origins of thermal curing date back to the 1930s when it was first utilized for manufacturing precast concrete components [157]. Over time, advancements in technology have introduced various heating techniques, including steam curing, microwave heating, and electric heating, which have broadened its application and efficiency.

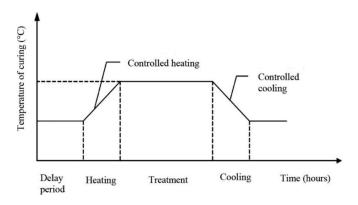


Figure 2.28: Schematic diagram of the steam-curing process [159].

2.4.1.2 Mechanisms of Heat Transfer and Temperature Dynamics

Heat transfer during thermal curing primarily occurs through conduction, convection, and radiation. The temperature distribution within the concrete during curing is influenced by multiple factors, such as the size and shape of the concrete element, the type and proportion of cement and supplementary cementitious materials, the water-to-binder ratio, and the specific curing temperature and duration.

The exothermic hydration of cement serves as the primary heat source in thermal curing, generating internal heat that propagates through the concrete matrix and creates temperature gradients within the structure [79], [160]. Factors such as the thermal conductivity, specific heat capacity, and thermal diffusivity of the concrete play a significant role in determining the rate of heat transfer and the resulting temperature distribution.

The thermal curing process can be divided into three distinct stages: heating, isothermal, and cooling. During the heating stage, the temperature rises rapidly to the desired level, followed by the isothermal stage, where a constant elevated temperature is maintained. Finally, the cooling stage ensures a controlled reduction in temperature. These stages, along with their respective durations and temperature levels, can be tailored to meet specific performance requirements for concrete properties.

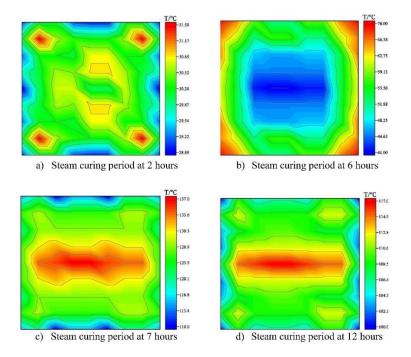


Figure 2.29: Internal temperature distribution in concrete samples at different steam curing durations: (a) 2 hours, (b) 6 hours, (c) 7 hours, and (d) 12 hours [161].

2.4.2 Heat Treatment Methods and Their Impact on Concrete Properties

2.4.2.1 Steam and Hot Water Curing: Processes, Equipment, and Benefits

Steam and hot water curing are widely adopted methods for expediting the concrete curing process, particularly in precast applications. Steam curing involves subjecting concrete elements to saturated steam in a controlled environment, which ensures high humidity and elevated temperatures [162]. This approach is especially effective during the early stages of curing, as it accelerates the hydration process, resulting in higher early-age strength and shorter setting times. Equipment commonly used for steam curing includes steam generators, curing chambers, and advanced temperature control systems to ensure uniform heat distribution across the concrete elements [162].

Hot water curing, by contrast, involves submerging concrete elements in hot water or applying hot water through spraying. This method is particularly beneficial in cold climates where maintaining optimal curing temperatures is essential for achieving the desired mechanical properties of concrete. Both steam and hot water curing methods improve the concrete's microstructure by reducing porosity, thereby enhancing its durability.

Beyond improving mechanical strength, these curing techniques contribute significantly to the durability of concrete structures. For instance, steam curing has been shown to decrease the permeability of concrete, improving its resistance to harmful agents such as chlorides and sulfates [162]. Additionally, these methods offer economic benefits by shortening the time required for formwork removal and enabling faster project timelines.

2.4.2.2 Electrical and Infrared Heating: Mechanisms and Effectiveness

Electrical and infrared heating are innovative curing methods that employ distinct mechanisms to enhance the thermal treatment of concrete. Electrical heating utilizes electric currents to generate heat within the concrete, often through systems such as heating cables or conductive concrete mixtures. This technique ensures uniform heating and precise temperature control, which are crucial for optimizing hydration and minimizing thermal gradients that might otherwise lead to cracking [163].

Infrared heating, in contrast, uses infrared radiation to directly warm the surface of concrete elements. Its ability to deliver rapid and targeted heating makes it particularly advantageous for reducing curing times compared to traditional methods [164]. The effectiveness of infrared heating depends on variables such as the proximity of the heat source, the angle of radiation, and the thermal conductivity of the concrete surface [164].

Both methods have demonstrated substantial improvements in the mechanical properties of concrete.

2.4.3 Thermal Curing Applications and Challenges in HPC

2.4.3.1 Specific Considerations and Challenges for HPC with Mineral additions

A major challenge arises from the interplay between thermal curing and the hydration kinetics of mineral additions. While thermal curing accelerates the hydration process of Portland cement, it may hinder the pozzolanic activity of supplementary cementitious materials (SCMs) such as fly ash and silica fume [165] . Elevated curing temperatures can prompt rapid early hydration of Portland cement, leaving insufficient time for SCMs to participate effectively in the hydration reactions, potentially resulting in incomplete hydration and diminished

mechanical performance [82]. To address this issue, precise regulation of curing temperature and duration is necessary to ensure an optimal balance between rapid hydration and comprehensive reaction of all components.

The physical characteristics and reactivity of Mineral additions also play a significant role in the behavior of HPC under thermal curing. Finer mineral particles generally react more rapidly, contributing to accelerated strength development. However, the quick heat generation associated with such reactions can heighten the risk of thermal cracking, especially during the cooling phase [166]. Consequently, optimizing the particle size distribution of Mineral additions becomes crucial for minimizing these risks while enhancing concrete performance [166].

Thermal curing can also exacerbate issues related to shrinkage and cracking in HPC, particularly during the early stages of curing. High temperatures, combined with the use of mineral additions, can intensify drying shrinkage, especially in large-scale applications where restrained conditions generate tensile stresses that may lead to cracking [165]. Effective curing practices that reduce moisture loss and regulate internal temperature gradients are therefore imperative to mitigate these challenges [165].

Additionally, the compatibility of various Mineral additions with thermal curing requires careful evaluation, as their thermal stability and reactivity can significantly influence the performance of HPC. Certain additives may release moisture during curing, altering the hydration dynamics and potentially causing inconsistencies in strength and durability outcomes [165]. A thorough understanding of the interactions between thermal curing environments and specific Mineral additions is essential for optimizing concrete performance.

In summary, while thermal curing offers substantial benefits for improving the properties of high-performance concrete, particularly in conjunction with mineral additions, it also introduces technical challenges that necessitate careful management. Addressing these challenges through the development of optimized curing protocols, strategic selection of mineral additions, and an in-depth understanding of their behavior under thermal conditions is vital for the successful application of thermal curing in HPC.

Table 2.11: Application scope of various thermal treatment methods in concrete production [167].

Element Size	Factory	Factory	Construction	Construction
	- Small	– Large	Site – Small	Site – Large
Treatment Method				
Utilization of hydration heat		+		
Mixing heat application		++		
Steam treatment (atmospheric pressure)	++	++	+	
Steam treatment (under pressure)	+	++		
Hot air treatment	+	++	+	
Formwork heating	++	++	++	
Hot water curing	+		++	
Infrared radiation	+			
Electric heating	++	++		
High-frequency heating				

2.4.4 Challenges, Limitations, and Environmental Impact of Thermal Curing

2.4.4.1 Energy Consumption, Environmental Considerations, and Temperature Control

Thermal curing techniques are effective for improving the early-age properties of concrete but are often associated with high energy demands and environmental concerns. The energy required to maintain elevated temperatures during curing is particularly significant in large-scale applications like mass concrete structures. For example, the heat generated by cement hydration can exceed 70°C, necessitating additional energy to regulate curing conditions. This raises sustainability concerns, especially in light of global initiatives to curtail energy use and reduce carbon emissions within the construction sector.

Beyond energy demands, the environmental impact of thermal curing is substantial. The reliance on fossil fuels for heating contributes to greenhouse gas emissions, while thermal stresses during curing can lead to increased cracking and structural degradation, adversely affecting the long-term performance of concrete [35]. Effective temperature regulation is vital to mitigate these issues, yet achieving uniform heat distribution in large concrete elements poses significant challenges. Uneven temperature gradients can induce thermal stresses that surpass the tensile strength of concrete, leading to cracking and structural vulnerabilities.

To address these challenges, several strategies have been proposed. The inclusion of phase change materials (PCMs) can help stabilize temperature fluctuations during curing [168]. Additionally, optimizing concrete mixes by incorporating supplementary cementitious materials can reduce the heat of hydration, thereby lowering energy requirements and minimizing environmental impacts. Advanced monitoring systems for real-time temperature control can further enhance curing efficiency and reduce energy consumption.

2.5 Advanced Characterization and Analytical Approaches for HPC with Supplementary Cementitious Materials

2.5.1 Role and Importance of Characterization Techniques for HPC Performance

The incorporation of supplementary cementitious materials (SCMs) in high-performance concrete (HPC) necessitates advanced characterization techniques to comprehensively evaluate its performance. These methods are vital for analyzing microstructural transformations and mechanical properties influenced by mineral additions. For instance, reflectance spectroscopy has been applied to monitor the compressive strength of HPC in situ, elucidating the correlation between microstructural attributes and mechanical behavior [169]. Additionally, machine learning methodologies have emerged as powerful tools for modeling and predicting the properties of both fresh and hardened concrete, facilitating the optimization of mix designs [170].

Non-destructive testing (NDT) techniques, such as ultrasonic pulse velocity and electromagnetic evaluations, also play a pivotal role in assessing the durability and structural integrity of concrete [171]. These methods enable the evaluation of critical parameters, including water content and porosity, which are key predictors of long-term performance under varying environmental conditions.

2.5.2 Analytical and Thermal Characterization Techniques for SCMs

2.5.2.1 Chemical, Physical, and Thermal Properties Analysis

The application of analytical and thermal characterization techniques is fundamental to understanding the chemical, physical, and thermal properties of supplementary cementitious materials (SCMs) used in high-performance concrete (HPC). These methods are critical for assessing how SCMs influence hydration processes, mechanical strength, and overall durability. Among these techniques, X-ray diffraction (XRD), thermogravimetric analysis (TGA), and differential scanning calorimetry (DSC) are extensively employed to evaluate the reactivity and performance of SCMs in cementitious systems.

X-ray diffraction (XRD) serves as a primary tool for identifying the mineralogical composition of SCMs, offering valuable insights into their expected behavior in concrete. The chemical composition of materials plays a pivotal role in determining their degree of reaction and, by extension, the mechanical properties of the resulting concrete [172]. The proportions of key oxides, including SiO₂, Al₂O₃, and CaO, significantly influence the pozzolanic activity of these materials and their compatibility with Portland cement [172].

Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) are essential for examining the thermal stability and phase transitions of SCMs. These methods enable the assessment of decomposition temperatures and thermal behavior under diverse conditions, providing critical information for their application in high-temperature environments. However, specific supporting references for TGA and DSC insights were not identified in the provided sources.

Advanced techniques such as scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) further complement the characterization process. These methods allow for detailed analysis of the microstructure of SCMs, including particle morphology, surface characteristics, and porosity. Such features are crucial for understanding the rheological behavior and workability of concrete mixtures, particularly in HPC applications [172].

2.5.3 Microstructural and Imaging Techniques for SCMs in HPC

2.5.3.1 X-Ray and Neutron Tomography, SEM, TEM, and AFM

The exploration of high-performance concrete (HPC) incorporating supplementary cementitious materials (SCMs) relies heavily on advanced microstructural and imaging techniques to analyze the interactions between SCMs and the cement matrix. Methods such as X-ray and neutron tomography, scanning electron microscopy (SEM), transmission electron

microscopy (TEM), and atomic force microscopy (AFM) provide invaluable insights into the microstructural properties that influence the mechanical performance and durability of concrete.

2.5.3.1.1 X-ray and Neutron Tomography

X-ray and neutron tomography are non-invasive imaging methods that enable detailed visualization of the internal structure of concrete without altering its physical integrity. These techniques are particularly useful for examining the distribution and connectivity of pores and aggregates within the concrete matrix, which are key factors affecting the material's behavior under mechanical stress and environmental exposure [173]. For example, X-ray computed tomography (CT) has proven effective in capturing microstructural changes in concrete exposed to elevated temperatures, offering detailed insights into pore network evolution and crack propagation [173].

2.5.3.1.2 Scanning Electron Microscopy (SEM)

SEM is a crucial tool for investigating the surface morphology and microstructural interactions between SCMs and the cement matrix. With its high-resolution imaging capabilities, SEM reveals intricate details about particle distribution, voids, and the development of hydration products such as calcium silicate hydrate (C-S-H) [174]. This technique has been instrumental in demonstrating how SCMs like silica fume and fly ash enhance the properties of concrete by filling voids and refining the microstructure, thereby improving mechanical strength and durability [174].

2.5.4 Statistical and Modeling Approaches in HPC Characterization

2.5.4.1 Design of Experiments (DOE), Factorial Designs, and Response Surface Methodology (RSM)

Statistical methodologies, including Design of Experiments (DOE) and Response Surface Methodology (RSM), are increasingly vital for the systematic characterization of High-Performance Concrete (HPC) incorporating Supplementary Cementitious Materials (SCMs). DOE offers a structured framework for conducting experiments, enabling researchers to efficiently examine the effects of multiple variables and their interactions. This approach is particularly valuable for optimizing concrete mixtures to achieve specific performance outcomes. Within DOE, factorial designs allow for the simultaneous assessment of multiple factors, uncovering interactions that might remain undetected through simpler univariate analyses [175], [176].

Factorial design techniques have been widely employed to evaluate the mechanical properties of concrete mixtures containing SCMs like fly ash and silica fume. Full and fractional factorial experiments are commonly used to reduce the experimental workload while still yielding reliable insights into how mix components interact [177], [178]. These methods enhance the understanding of material behavior and support the development of predictive models that inform future mix design strategies.

RSM complements DOE by enabling the optimization of response variables based on the data obtained from experiments. Using polynomial regression models, RSM captures the relationships between input variables and desired outcomes, such as compressive strength and durability. This approach has been successfully applied to optimize concrete mixtures, demonstrating improvements in performance metrics while reducing material costs. The method is particularly effective in identifying conditions that maximize performance or sustainability in HPC formulations.

2.5.4.2 Statistical Software and Computational Tools for Analysis

The adoption of statistical software platforms such as JMP and Minitab has significantly advanced the analysis of experimental data in concrete research. These tools facilitate complex statistical analyses, including factorial ANOVA and regression modeling, which are integral to interpreting results from DOE and RSM studies [178]. Among these, JMP is particularly noted for its intuitive interface and robust analytical capabilities, making it accessible to researchers with varying levels of statistical expertise.

Moreover, these software platforms enable the creation of detailed graphical representations that enhance the visualization and understanding of interactions between variables. Features like contour plots and surface plots provide insights into how different SCMs affect concrete properties, aiding in the decision-making process for optimizing mix designs. For example, JMP facilitates the generation of these visual tools, supporting the interpretation of experimental data and improving the efficiency of the optimization process.

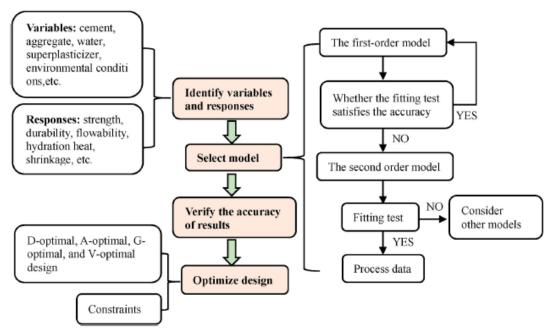


Figure 2.30: Stepwise procedure for Response Surface Methodology (RSM) design optimization [179].

2.6 Synthesis and Research Gaps

2.6.1 Summary of Key Findings in HPC with Mineral Additions

2.6.1.1 Fresh State Properties, Curing, and Thermal Treatment Effects

High-performance concrete (HPC) is distinguished by its exceptional mechanical performance and durability, which are greatly influenced by the addition of mineral materials. The fresh state properties of HPC, including workability and rheology, are pivotal in ensuring proper placement and compaction. Supplementary cementitious materials (SCMs) such as fly ash, silica fume, and ground granulated blast furnace slag (GGBS) are known to enhance workability by optimizing the water-binder ratio and improving particle packing density [59], [102]. These modifications contribute to a more fluid and homogeneous mix, which is particularly advantageous in complex structural applications.

The curing process is equally critical in determining the strength and durability of HPC. Thermal curing techniques, such as steam curing, have been widely reported to expedite hydration and increase early-age strength [180]. The efficiency of these methods, however, is strongly influenced by the type and dosage of mineral additions. For example, fly ash is noted for its ability to reduce the heat of hydration, thereby lowering peak temperatures during curing and mitigating the risk of thermal cracking [95], [181]. Conversely, silica fume enhances the microstructure of the concrete, contributing to greater durability and resistance to environmental stresses.

2.6.1.2 Influence of SCMs on Mechanical Properties and Durability

The mechanical performance of HPC can be significantly improved through the deliberate incorporation of SCMs. Studies have consistently shown that materials like fly ash and GGBS contribute to substantial enhancements in compressive and tensile strength [102], [182]. These improvements are attributed to the pozzolanic activity of SCMs, which fosters the formation of additional calcium silicate hydrates (C-S-H), thereby increasing the material's load-bearing capacity and overall structural resilience [182]. As illustrated in Figure 2.36, cement hydration leads to the formation of two distinct types of C-S-H gels, which play a crucial role in strength development and durability. The denser and more refined C-S-H structure resulting from SCM incorporation not only enhances mechanical performance but also reduces shrinkage and cracking, both of which are essential for maintaining long-term durability in concrete structures.

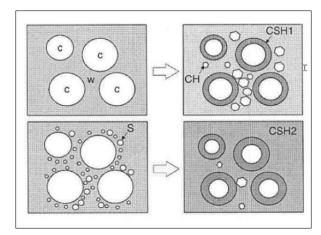


Figure 2.31: Schematic representation of the formation of two types of C-S-H gels in cement hydration [183].

In terms of durability, SCMs play a critical role in enhancing resistance to various deterioration mechanisms, including chloride ion penetration, sulfate attack, and freeze-thaw cycles. The microstructural densification achieved through SCM integration results in reduced permeability, which is vital for protecting steel reinforcement against corrosion [184]. Moreover, the incorporation of SCMs has been shown to significantly improve the long-term performance of HPC in harsh environments, such as marine and industrial settings, where exposure to aggressive agents like chlorides and sulfates is common [40], [184].

2.6.2 Integrative Analysis and Comparative Performance of Pozzolanic Additives in HPC

Table 2.12: Comparative evaluation of supplementary cementitious materials (SCMs) in high-performance concrete (HPC)

SCM Type	Distinguishing	Advantages in HPC	Limitations
	Features		
Fly Ash	High silica and alumina	Improves workability,	Variability in
	content, spherical	enhances long-term	composition, delayed
	particle morphology,	mechanical properties,	early-age strength
	moderate pozzolanic	reduces permeability,	development.
	reactivity.	and limits heat	
		generation during	
		hydration.	
Silica Fume	Extremely fine particles,	Significantly increases	Increases water
	elevated pozzolanic	compressive strength,	demand, may
	activity, high amorphous	densifies	contribute to early-age
	silica content.	microstructure, and	shrinkage.
		enhances resistance to	
		aggressive	
		environments.	
Ground Granulated	Rich in calcium and	Boosts long-term	Slower early strength
Blast Furnace Slag	silica, requires activation	durability, improves	development, requires
(GGBFS)	for optimal reactivity.	sulfate resistance,	precise curing
		decreases permeability,	conditions.
		and minimizes thermal	
		gradients.	
Natural Pozzolans	Variable silica content,	Provides cost-effective	Inconsistent quality,
	slower pozzolanic	alternatives, reduces	requires assessment for
	reactivity.	greenhouse gas	effective application.
		emissions, enhances	

durability under aggressive exposures.

Blended SCMs Synergistic Improves workability, Complex optimization

combinations of two or reduces shrinkage, required in mix design.

more SCMs (e.g., fly ash optimizes mechanical

+ slag, silica fume + fly properties, and

ash). leverages

complementary

reactivity.

2.6.3 Leveraging Algerian SCMs: Andesite, Calcined Marl, and Natural Pozzolan

In Algeria, the focus on local resources such as andesite, calcined marl, and natural pozzolan has revealed their significant potential as SCMs for high-performance concrete. Andesite, volcanic rock rich in silica and alumina, exhibits promising pozzolanic properties. Its incorporation into concrete has been found to enhance compressive strength and durability, offering an effective alternative to conventional SCMs. The pozzolanic reaction of andesite with calcium hydroxide leads to the production of additional C-S-H, which refines the concrete's microstructure and improves its overall performance.

Calcined marl is another locally available material with substantial potential as an SCM. The calcination process transforms marl into a reactive pozzolan capable of significantly improving concrete's mechanical properties. Research findings indicate that calcined marl reduces permeability and increases resistance to sulfate attack, contributing to the extended service life of concrete structures. The material's ability to reduce capillary porosity through secondary C-S-H gel formation further enhances the durability of HPC.

Natural pozzolan, derived from Algeria's volcanic deposits, has also been extensively investigated for its efficacy in HPC formulations. Its high silica and alumina content enable pozzolanic reactions that result in the formation of additional C-S-H, thereby increasing strength and resistance to chemical attacks. Substituting a portion of Portland cement with natural pozzolan has demonstrated significant improvements in compressive strength and durability, making it an effective and sustainable option for concrete production. Furthermore,

the local availability of natural pozzolan supports sustainable construction practices by reducing the carbon emissions associated with cement production.

Table 2.13: Properties, pozzolanic activity, and effects of Algerian supplementary cementitious materials (SCMs) on high-performance concrete (HPC)

SCM Type	Key Properties	Pozzolanic	Influence on HPC	Sustainability
		Reactivity	Performance	Benefits
Andesite	A volcanic rock	Reacts with	Increases	Promotes the use of
	rich in silica and	calcium	compressive	locally sourced
	alumina,	hydroxide to	strength and	materials, minimizing
	abundant in	generate	structural integrity.	the dependency on
	Algeria	additional	- Enhances	imported SCMs.
		calcium	durability by	- Reduces the carbon
		silicate	refining the	emissions associated
		hydrates (C-	concrete's	with transportation and
		S-H),	microstructure.	production.
		enhancing matrix	- Provides	
		densificatio	resistance to	
		n.	cracking and	
			environmental	
			stressors.	
Calcined Marl	A sedimentary	Reduces	Enhances sulfate	Utilizes Algeria's
	material	permeabilit	resistance and	abundant marl
	activated	y and fosters	mitigates chemical	deposits, lowering
	through thermal	the	attacks.	material acquisition
	calcination,	formation of	- Reduces porosity,	costs and energy
	yielding a	secondary	improving the	consumption.
	highly reactive	C-S-H,	long-term	- Supports eco-friendly
	pozzolanic	which	durability of HPC.	-
	phase.	contributes	duratinity of the C.	concrete production
		to pore		

		structure	- Increases	with a reduced carbon
		refinement.	mechanical	footprint.
			properties such as	
			compressive	
			strength.	
Natural Pozzolan	Volcanic ash	Reacts with	Improves	Reduces the
	with high silica	calcium	compressive	proportion of Portland
	and alumina	hydroxide,	strength and long-	cement required in
	content,	forming	term durability.	mixes, substantially
	sourced from	additional	- Enhances	lowering CO ₂
	Algeria's	C-S-H and	resistance to	emissions.
	volcanic	reducing		- Encourages the use of
	regions	overall	environmental	renewable and
		porosity,	deterioration.	naturally occurring
		which	actionalion.	resources.
		enhances.	- Improves	lebourees.
			workability and	

reduces shrinkage.

2.6.4 Justification and Significance of the Present Study

2.6.4.1 Addressing Research Gaps in SCM Use for HPC

This study seeks to address critical gaps in understanding the role of supplementary cementitious materials (SCMs) in high-performance concrete (HPC). While existing research highlights the benefits of SCMs, such as improved mechanical properties and enhanced durability, limited attention has been given to the specific interactions between different Mineral additions and the curing processes of HPC. Most studies focus on conventional SCMs like fly ash and silica fume, overlooking the potential of regionally available materials. This research addresses this void by investigating the impact of Algerian mineral additions, such as calcined clay and andesite, alongside natural pozzolan, on the curing kinetics, rheological behavior, and long-term durability of both heat-treated and non-heat-treated HPC.

2.6.4.2 The Role of Local Mineral additions in Sustainability and HPC Performance

The importance of utilizing local Mineral additions in HPC extends beyond performance enhancement, encompassing significant environmental and sustainability benefits. Integrating indigenous pozzolans and SCMs reduces the carbon footprint of concrete production by lessening the dependence on traditional Portland cement. This study underscores the potential of materials abundant in Algeria, such as calcined marl and andesite, which exhibit strong pozzolanic activity and can significantly improve HPC performance [123].

Using local Mineral additions not only supports regional economic development by utilizing domestic resources but also curtails transportation emissions linked to importing conventional SCMs. By demonstrating the ability of these materials to enhance rheological properties and durability, this research promotes their wider application in the construction sector, advancing more sustainable and environmentally friendly production practices.

2.6.4.3 Advancing HPC Research and Sustainable Construction Practices

This study contributes to the field of HPC and sustainable construction on multiple fronts. First, by examining the influence of Mineral additions on the curing behavior and rheology of HPC, the research offers valuable insights into optimizing concrete formulations to achieve superior performance. The findings will not only expand scientific understanding of SCM-cement interactions but also provide actionable knowledge for engineers and practitioners to refine their practices.

Second, the focus on sustainability aligns with global efforts to mitigate the environmental impact of construction materials. By showcasing the potential of locally available SCMs, such as andesite and calcined marl, as viable substitutes for traditional materials, this research advances discussions on sustainable construction and the circular economy. The outcomes are expected to guide policy frameworks and foster the adoption of eco-friendly alternatives in the construction industry, promoting resilient and sustainable infrastructure development.

2.6.5 Conclusion

This research addresses key gaps in the understanding of SCM applications in HPC, underscores the importance of local Mineral additions for promoting sustainability, and offers significant contributions to advancing high-performance concrete technology. By providing deeper insights into SCM-cement interactions and advocating for sustainable practices, the study aims to influence both scientific progress and industry adoption of environmentally responsible construction methodologies.

EXPERIMENTAL **PROGRAM** & **METHODOLOGY**





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CHAPTER 3:

EXPERIMENTAL PROGRAM AND METHODOLOGY

3 EXPERIMENTAL PROGRAM AND METHODOLOGY

3.1 Research Framework and Objectives

3.1.1 Scope of the Study and Research Approach

The development of high-performance concrete (HPC) has gained significant attention in recent years due to its superior mechanical properties and durability. Among the various strategies to enhance HPC, the incorporation of supplementary cementitious materials (SCMs) is particularly promising. While traditional SCMs such as fly ash, silica fume, and ground granulated blast furnace slag (GGBS) have been widely studied, the potential of local Mineral additions remains an area requiring further exploration.

This study focuses on the valorization of two Algerian mineral resources—andesite and calcined marl—as SCMs in HPC formulations, particularly under heat-treated and untreated conditions. The primary objective is to evaluate their pozzolanic activity, influence on fresh and hardened concrete properties, and durability performance. Given the sustainability benefits associated with reducing clinker content in cementitious materials, this research aligns with contemporary efforts to promote eco-friendly and resource-efficient construction materials.

A multi-disciplinary experimental approach has been adopted, integrating materials characterization, mix design optimization, and mechanical/durability performance assessments. The systematic evaluation of andesite and calcined marl is intended to provide insights into their chemical, mineralogical, and microstructural behavior, facilitating a better understanding of their role in HPC performance enhancement. Furthermore, the study investigates how these natural pozzolans interact with different curing conditions, including steam curing and ambient curing, which are essential for optimizing their practical application in construction.

3.1.2 Key Research Questions and Experimental Hypotheses

Building upon the research gaps identified in the literature review, this study seeks to answer the following key research questions:

What are the chemical, mineralogical, and microstructural characteristics of andesite and calcined marl, and how do they compare to conventional pozzolanic materials?

How do these local Mineral additions influence the fresh state properties of HPC, including workability, viscosity, and setting time?

To what extent do andesite and calcined marl contribute to strength development in HPC, and how does this compare between heat-treated and non-heat-treated conditions?

What are the durability implications of incorporating these materials in HPC, particularly in terms of porosity, water absorption, sulfate resistance, and microstructural integrity?

Can a scientific correlation be established between the thermal activation of calcined marl and its enhanced pozzolanic activity in HPC?

To address these questions, the study is guided by the following hypotheses:

H1: Andesite and calcined marl exhibit significant pozzolanic activity, contributing to hydration reactions and microstructural densification in HPC.

H2: The addition of these SCMs enhances the workability and packing density of fresh HPC due to their particle morphology and specific surface area.

H3: Strength development in HPC is positively influenced by the pozzolanic reaction of andesite and calcined marl, with notable differences between heat-treated and non-heat-treated conditions.

H4: The inclusion of andesite and calcined marl improves the durability characteristics of HPC by reducing porosity, refining pore structure, and enhancing sulfate resistance.

H5: Calcination significantly enhances the reactivity of natural marl, leading to a more amorphous structure and superior cementitious performance.

3.1.3 Workflow and Experimental Stages

The experimental program follows a structured workflow, beginning with the selection and characterization of andesite and calcined marl through geological, mineralogical, and chemical analyses to assess their pozzolanic potential. Next, HPC mix design optimization is conducted using granulometric analysis, superplasticizer dosage adjustments, and established proportioning methods to ensure optimal workability and mechanical performance. Concrete specimens are then cast and subjected to two curing regimes—standard ambient curing and

steam curing—to evaluate the influence of thermal treatment. The performance of HPC is assessed through fresh state tests (workability and density), mechanical strength evaluations at multiple ages, and durability assessments focusing on porosity, sulfate resistance, and microstructural integrity. Finally, statistical and computational analysis is applied, using design of experiments (DOE) and regression modeling to establish correlations between material properties and HPC performance, providing a robust understanding of the impact of these Mineral additions in sustainable concrete applications.

3.2 Materials Characterization

3.2.1 Cementitious Materials and Supplementary Additives

3.2.1.1 Ordinary Portland Cement: Characteristics and Suitability

In this study, the primary cementitious binder employed is Ordinary Portland Cement (OPC), classified as CEM I 42.5R. This designation indicates a high early strength class, making it particularly suitable for applications where rapid formwork removal and early mechanical performance are critical—key requirements in the production of high-performance concrete (HPC). The selected OPC, sourced from the Biskria Cement Plant in Algeria, conforms to the specifications established by the Algerian standard NA 442-2013 [185].

The cement is characterized by an absolute (true) density of 3.12 g/cm³ and a Blaine fineness of 3888 cm²/g, indicative of a high degree of particle refinement that contributes to enhanced hydration kinetics and strength development. These properties, along with its verified chemical and physical composition (as detailed in Tables 3.1 and 3.2), confirm its appropriateness for cementitious mixtures designed for accelerated strength development

3.2.1.2 Locally Sourced Pozzolanic Additives: Andesite and Calcined Marl

This study investigates the potential of andesite (AND) and calcined marl (CM) as alternative supplementary cementitious materials (SCMs). These locally sourced mineral additions were selected based on their abundance, reactivity, and potential for partial cement replacement. Their performance was benchmarked c Benisaf, a well-established SCM in Algerian concrete research [186]. The effects of these materials on workability, strength development, and durability were assessed under both ambient and heat-treated curing conditions.

3.2.1.3 Origin and Geological Context of Raw Materials

3.2.1.3.1 Source Areas

Andesite (AND): Extracted from the Ahmer El Aïn quarry in Tipaza, Algeria (36°27'54"N, 2°32'57"E), a region recognized for its high-strength andesitic formations, suitable for construction applications [187].



Figure 3.1: Satellite View of the Ahmer El Aïn Quarry – Source of Andesite in Tipaza, Algeria.



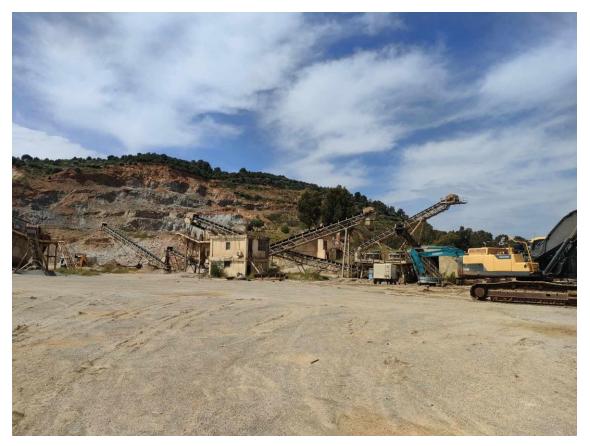


Figure 3.2: Field View of the Ahmer El Aïn Quarry – Andesite Extraction Site.

Natural Marl (NM): Sourced from the Theniet Mouloutou deposit near Sétif, Algeria (36°19'22"N, 5°28'44"E), covering 48 hectares. The marl from this region exhibits high pozzolanic reactivity upon calcination, making it an ideal SCM candidate [11].





Figure 3.3: Satellite View of the Ain El Kebira Deposit – Source of Natural Marl in Sétif, Algeria.





Figure 3.4: On-Site View of the Ain El Kebira Natural Marl Deposit.

Natural Pozzolan (NPZ): Obtained from the Bouhamidi deposit, south of Beni-Saf, Algeria (35°17′09″N, 1°24′26″W). This siliceous volcanic ash is known for its high reactivity with lime, essential for improving cementitious reactions [188].

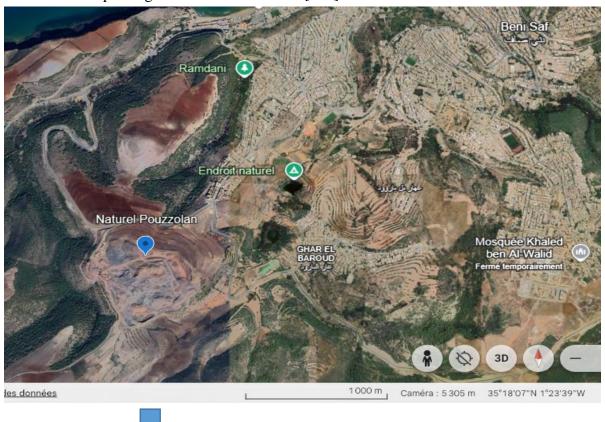




Figure 3.5: Satellite View of the Natural Pozzolan Deposit in Beni Saf, Algeria.

A map depicting these quarry locations is provided in Figure 3.6, illustrating the spatial distribution of these materials across Algeria.

The raw materials were extracted from distinct geological formations across Algeria:

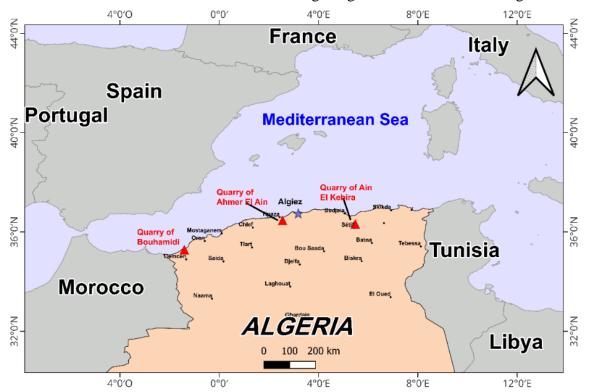


Figure 3.6: Geographic locations of the Ahmer El Aïn, Theniet Mouloutou, and Bouhamidi quarries in Algeria.

3.2.1.3.2 Geological Characteristics

Andesite (AND): Geological Formation and Mineralogical Composition

The Ahmer El Aïn quarry is located within a vast andesite-rich geological structure, which is part of a broader volcanic terrain shaped by multiple magmatic events. Andesite, a fine-grained extrusive igneous rock, is predominantly composed of plagioclase feldspar, pyroxene, and amphibole, contributing to its high compressive strength and durability, properties that make it particularly suitable for high-performance concrete (HPC) applications. The surrounding geological environment is characterized by Senonian marls and Quaternary alluvial deposits, reflecting a long history of fluvial sedimentation and volcanic activity. The interplay between ancient sedimentary layers and more recent volcanic formations has resulted in a heterogeneous soil profile, ranging from compact, calcium-rich marl to loose, alluvial deposits, which further highlights the complex geological evolution of the region. This diverse mineralogical setting

enhances the structural integrity and reactivity of andesite, reinforcing its potential as an effective SCM in cementitious systems.

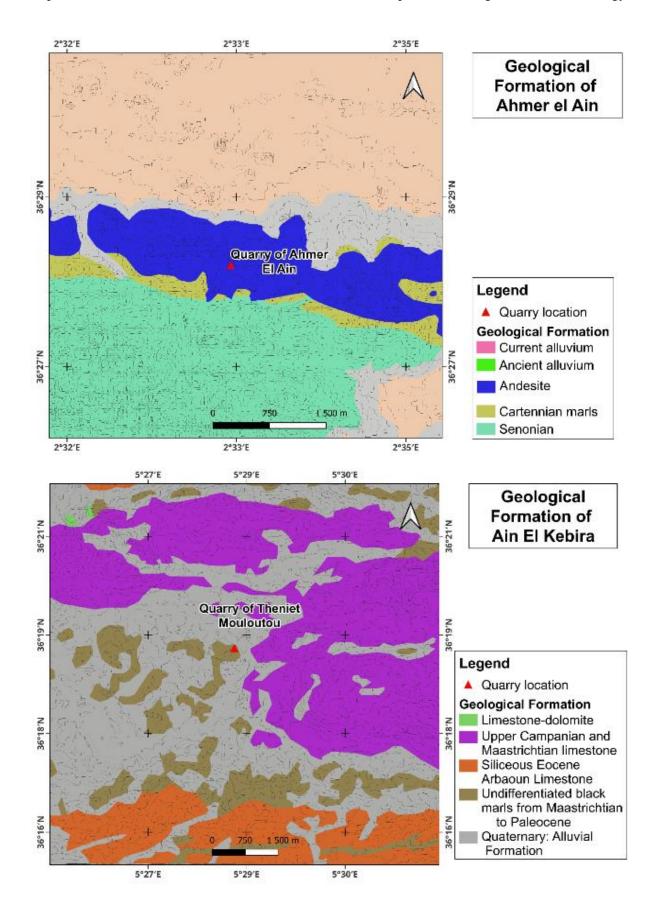
Natural Marl (NM): Stratigraphy and Depositional Environment

The Theniet Mouloutou quarry, located in a region dominated by black marls of Maastrichtian—Paleocene age, represents a fine-grained sedimentary formation rich in clay minerals and organic matter. These marls were formed through marine, lacustrine, and fluvial depositional processes, leading to the interbedding of calcareous and siliceous sediments. The presence of Upper Campanian and Maastrichtian limestones, along with Quaternary alluvial formations, suggests a complex stratigraphic evolution influenced by transgressive and regressive marine conditions. The high clay content and fine particle size of these marls contribute to their enhanced pozzolanic reactivity when subjected to thermal activation, making them particularly suitable for use in blended cement formulations. The mineralogical transformations resulting from calcination at optimized temperatures further enhance the reactive silica and alumina content, strengthening the material's ability to improve concrete durability and long-term mechanical performance.

Natural Pozzolan (NPZ): Volcanic Origin and Reactivity Potential

The Bouhamidi quarry is situated within Paleocene basaltic lava flows, a geological setting characterized by volcaniclastic deposits rich in siliceous volcanic glass. This formation is the result of intense volcanic activity in the Beni Saf region during the Paleocene, which contributed to the accumulation of pyroclastic material, including volcanic ash and fragmented lava. The mineral composition of this natural pozzolan includes amorphous silica, feldspar, and iron-bearing phases, which significantly enhance its reactivity with calcium hydroxide during the cement hydration process. The porous, coarse-grained texture of the deposit facilitates its interaction with water and cementitious binders, improving the mechanical performance and durability of concrete. The presence of silica-rich volcanic glass ensures its high pozzolanic activity, making it a valuable component in hydraulic cement production.

The geological formations of these quarries, as depicted in Figure 3.7, underscore the diverse mineralogical origins of andesite, natural marl, and natural pozzolan. Their distinct compositional and structural characteristics contribute to their effectiveness as supplementary cementitious materials, enhancing the mechanical properties, durability, and sustainability of high-performance concrete formulations.



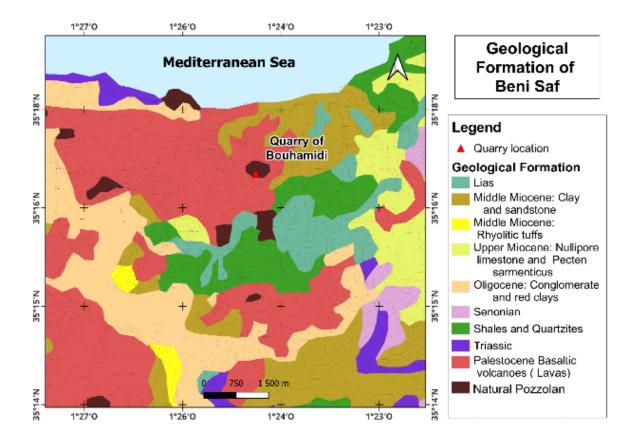


Figure 3.7: Geological formations of the Ahmer El Aïn, Theniet Mouloutou, and Bouhamidi quarries.

3.2.1.4 Milling and Processing: From Quarry Extraction to Fine Powder

3.2.1.4.1 Extraction and Initial Sorting

The transformation of raw mineral resources into finely ground supplementary cementitious materials (SCMs) begins with the extraction phase. Large rock masses are excavated from designated quarries using controlled blasting or mechanical excavation techniques. Once extracted, the material undergoes an initial sorting process to remove unwanted impurities, ensuring that only high-quality mineral fractions are processed further. This extraction and sorting phase is illustrated in Figure 3.8, which depicts the raw state of andesite, natural marl, and natural pozzolan before comminution.

Chapter 3

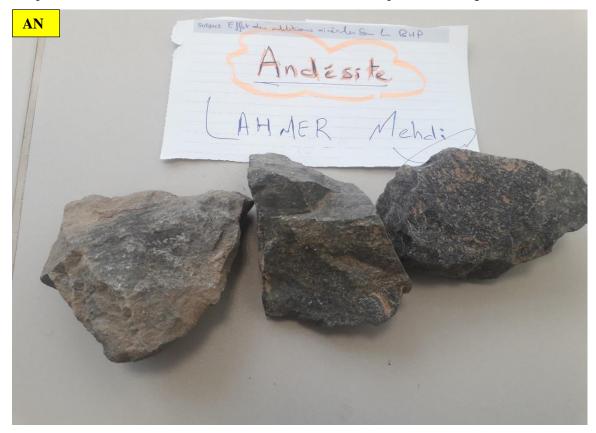










Figure 3.8: Raw Mineral Samples Before Processing – Andesite, Natural Pozzolan, and Natural Marl.

3.2.1.4.2 Primary and Secondary Comminution

The comminution process, aimed at reducing particle size and increasing specific surface area, is critical in preparing the Mineral additions for cementitious applications. Initially, the quarried material undergoes primary crushing using jaw crushers, breaking down large blocks into smaller, more manageable fragments. The next steps depend on the mechanical properties of each material:

Andesite Processing: Given its high compressive strength, andesite requires an additional secondary crushing stage, typically performed using impact crushers or cone crushers, to achieve further granulometric refinement.

Natural Marl Processing: Due to its friable nature and lower mechanical strength, natural marl undergoes a single-stage crushing process, as excessive mechanical action could cause unnecessary powdering.

Natural Pozzolan Processing: Depending on its mineralogical composition and hardness, natural pozzolan may require either a single-stage or multi-stage crushing process to achieve optimal size reduction.

This phase of particle size reduction is visually represented in Figure 3.9, illustrating the progression from raw rock fragments to crushed material before fine grinding.





Figure 3.9: Primary Crushing of Mineral additions—Initial Comminution Stage.

3.2.1.4.3 Drying and Moisture Control

To optimize grinding efficiency and prevent material agglomeration, a drying phase is necessary, particularly for moisture-retentive materials such as natural marl. The drying process is conducted in a laboratory drying oven at a controlled temperature, typically set between 105°C and 110°C, as shown in Figure 3.10. This temperature range ensures the effective removal of free moisture without inducing mineralogical alterations or premature chemical reactions.

The duration of drying depends on the initial moisture content and particle size distribution of the material. Proper drying enhances the flowability of the crushed material, reduces the risk of agglomeration during milling, and ensures consistency in the final powder characteristics. The effect of drying on the physical state of the crushed material can be observed in Figure 3.10, which compares raw, moisture-rich samples with fully dried samples ready for milling.





Figure 3.10: Laboratory Drying of Mineral additions—Moisture Removal Process.

3.2.1.4.4 Fine Grinding and Particle Refinement

Following initial size reduction and drying, the materials undergo fine grinding to achieve the target fineness necessary for optimal pozzolanic reactivity. The milling process is designed to maximize surface area while ensuring a controlled particle size distribution, which enhances

the reactivity of the supplementary cementitious materials (SCMs) in high-performance concrete (HPC).

This milling phase is performed using:

Ball Mills: A conventional grinding system where steel grinding media progressively reduce particle size through mechanical impact and attrition, ensuring uniform granulometry.

Vertical Roller Mills: An alternative milling system known for its superior energy efficiency and precise control over particle size distribution, making it suitable for achieving finely tuned fineness levels.

The grinding parameters, including rotation speed, grinding duration, and media composition, are meticulously adjusted to obtain the desired Blaine fineness, which directly influences the pozzolanic activity of the mineral additions. The effectiveness of grinding is closely monitored to ensure uniformity and minimize the presence of oversized particles.

The materials used in the milling process, including the grinding media and equipment, are illustrated in Figure 3.11, providing a detailed view of the tools involved in achieving fine powder refinement.









Figure 3.11: Equipment Used for Fine Grinding and Particle Refinement.

3.2.1.4.5 Quality Control: Fineness Evaluation

Fineness assessment is a key quality control measure to ensure the optimal performance of processed supplementary cementitious materials (SCMs). The Blaine fineness test, shown in Figure 3.12, is used to determine the specific surface area by measuring the air permeability of compacted powder samples. This test ensures that the milled materials achieve the required fineness for enhanced pozzolanic activity in cement-based applications.





Figure 3.12: Fineness Evaluation of Supplementary Cementitious Materials Using the Blaine Method.

3.2.1.4.6 Final Powder Characteristics

The processed mineral additions—andesite, natural marl, and natural pozzolan—exhibit distinct fineness and particle morphology, which directly influence their performance in high-performance concrete (HPC). The Blaine fineness values confirm that the grinding process achieves the required surface area for optimal pozzolanic activity.

A visual comparison of the final powders is presented in Figure 3.13, highlighting their refined texture and uniform particle distribution. These finely ground materials, optimized for cementitious applications, play a crucial role in enhancing the workability, mechanical strength, and durability of HPC mixtures.





Figure 3.13: Final Powder Characteristics of Processed Mineral Additions.

3.2.1.5 Thermal Activation of Natural Marl: Optimization and Reactivity Enhancement

The thermal activation of natural marl is a key process in enhancing its pozzolanic reactivity by inducing significant mineralogical and microstructural transformations. Calcination at an optimized temperature facilitates the dehydroxylation of clay minerals and the decomposition of carbonates, leading to the formation of a more reactive amorphous phase. In this study, the optimal calcination conditions were determined based on thermogravimetric analysis (TGA) and differential thermal analysis (DTA), ensuring maximum reactivity while avoiding excessive sintering. [189]

The pozzolanic activity of natural marl was significantly enhanced through calcination at 750°C, a temperature identified as optimal via TGA analysis [189]. The TGA curve (Figure 3.14) highlights a substantial weight loss between 365°C and 800°C, which corresponds to the elimination of bound water from clay minerals and the thermal decomposition of calcium carbonate (CaCO₃) into calcium oxide (CaO) and carbon dioxide (CO₂). These chemical transformations lead to the structural destabilization of the original crystalline phases, promoting the formation of an amorphous aluminosilicate matrix. The DTA curve (Figure 3.15) further confirms these transformations, revealing distinct endothermic peaks that correspond to the dehydroxylation and carbonate decomposition reactions.

To achieve an optimal balance between effective activation and preventing material sintering, the optimized thermal cycle is illustrated in Figure 3.16. Maintaining the calcination temperature at 750°C for two hours ensures sufficient energy input to disrupt the mineral lattice while preserving the desired reactivity. The resulting calcined marl exhibits improved physicochemical properties, including increased surface area and enhanced reactivity with calcium hydroxide in cementitious systems. These changes are further demonstrated through microstructural analysis, where Figure 3.17 illustrates the transformation of natural marl before and after calcination, highlighting the breakdown of the crystalline structure and the emergence of a more reactive phase.

To provide a comprehensive understanding of this thermal treatment, Figure 3.18 visually represents the complete calcination process, detailing each stage from raw natural marl to the final calcined product. The sequence illustrates the material in its initial state, its placement in a high-temperature furnace, the exposure to 750°C for two hours, and the resulting phase transformation, evidenced by the distinct color change of the treated material. This visual representation highlights the key physicochemical modifications occurring throughout the process, which directly contribute to the enhanced pozzolanic activity of calcined marl.

These findings underscore the critical role of thermal activation in improving the performance of natural marl as a supplementary cementitious material (SCM). By optimizing calcination

parameters, it is possible to maximize reactivity and enhance the material's contribution to highperformance concrete formulations.

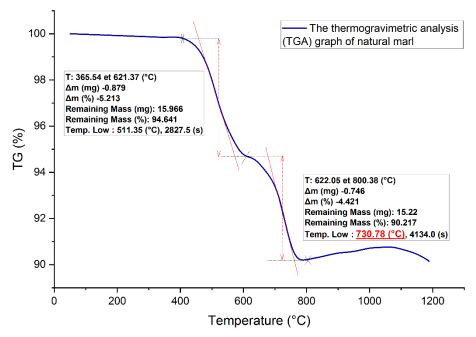


Figure 3.14: Results of Thermogravimetric Analysis (TGA) for Natural Marl.

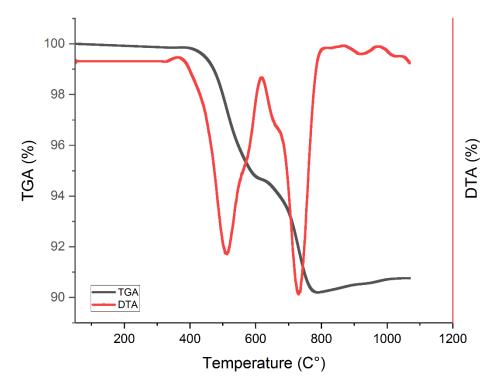


Figure 3.15: Thermogravimetric (TGA) and Differential Thermal Analysis (DTA) profiles of natural marl.

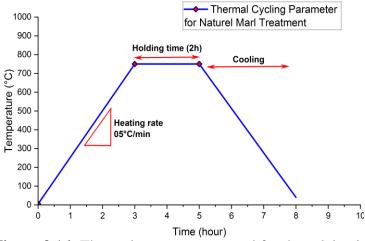


Figure 3.16: Thermal treatment protocol for the calcination of natural marl.



Figure 3.17: Morphological Changes in Natural Marl Before (B) and After (A) Calcination.

♣ Step 1: Raw Natural Marl – Initial State





♣ Step 2: Calcination Process at 750°C









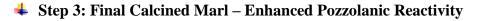




Figure 3.18: Thermal Activation Process of Natural Marl – From Raw Material to Calcined Product.

3.2.1.6 Characterization Techniques for Cementitious Materials

The evaluation of cementitious materials is crucial for determining their mineralogical, chemical, and physical characteristics, as these properties significantly impact their performance in high-performance concrete (HPC) mixtures. This research utilizes a combination of analytical techniques, including X-ray diffraction (XRD), X-ray fluorescence (XRF), scanning electron microscopy (SEM), and physical property measurements, to gain a thorough insight into the crystallinity, chemical composition, particle morphology, and surface area of the selected materials. The findings obtained through these characterization methods enable a detailed assessment of reactivity, compatibility, and potential enhancements in cementitious behavior when incorporating andesite and calcined marl as supplementary cementitious materials (SCMs). A summary of the key properties derived from these analyses is provided in Table 3.3, while Figures 3.13 and 3.20 depict the corresponding analytical results

3.2.1.6.1 Mineralogical Composition Assessment Using X-Ray Diffraction (XRD)

X-ray diffraction (XRD) analysis was conducted to determine the crystalline phases present in andesite, natural marl, calcined marl, and natural pozzolan, as their mineralogical structure significantly impacts their reactivity and cementitious properties. The diffraction patterns revealed that andesite consists predominantly of plagioclase feldspar and pyroxene, confirming its volcanic origin and structural stability. Natural marl exhibited significant peaks for calcite and quartz, indicative of its sedimentary nature and high calcium carbonate content. Following thermal activation, calcined marl showed a reduction in crystalline calcite peaks and an increase in amorphous silica phases, suggesting the formation of reactive pozzolanic compounds due to dehydroxylation and carbonate decomposition. The XRD patterns of natural pozzolan revealed a heterogeneous composition of quartz, feldspar, and hematite, reinforcing its suitability for cementitious applications. The mineralogical analysis provided critical insights into the reactivity potential of these SCMs, with calcined marl demonstrating enhanced pozzolanic properties due to its transition to a predominantly amorphous state, as illustrated in Figure 3.19, which presents the diffraction profiles of the analyzed materials.

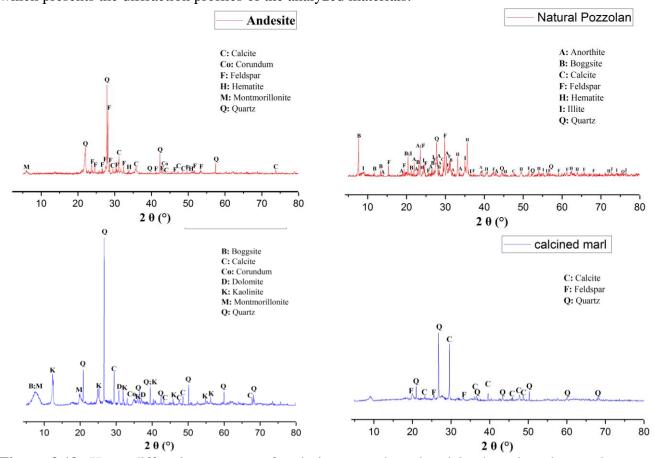


Figure 3.19: X-ray diffraction patterns of andesite, natural marl, calcined marl, and natural pozzolan.

3.2.1.6.2 Chemical Composition Analysis Using X-Ray Fluorescence (XRF)

X-ray fluorescence (XRF) spectrometry was performed to quantify the oxide compositions of the selected materials, as their chemical makeup directly influences their cementitious behavior and contribution to hydration reactions. The analysis confirmed that andesite contains a high proportion of silica (SiO₂: 65.55%), which enhances its potential for pozzolanic activity, while its moderate alumina (Al₂O₃: 12.28%) and iron oxide (Fe₂O₃: 6.23%) contents contribute to its ability to react with calcium hydroxide during the cement hydration process. Natural marl, due to its sedimentary nature, exhibited a high calcium oxide (CaO) content (12.59%), which can enhance its binding properties when blended with other cementitious materials. The calcined version of the marl showed an increase in reactive silica and alumina content, reinforcing its pozzolanic potential. Natural pozzolan displayed a balanced chemical composition of SiO₂ (55.45%) and Al₂O₃ (15.88%), which supports its use as an SCM for enhancing HPC durability and long-term performance. The detailed chemical compositions of all tested materials are summarized in Table 3.1, providing a comparative evaluation of their oxide content and potential cementitious contributions.

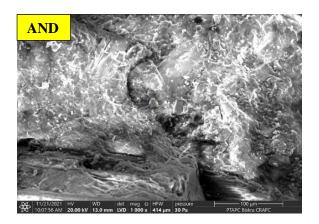
Table 3.1: Chemical composition of selected mineral additions.

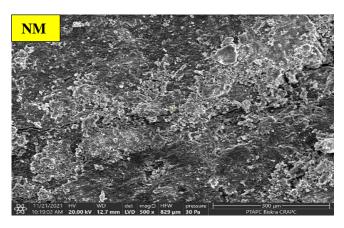
Chemical components (%)	С	AND	CM	NPZ
SiO ₂	19.52	65.55	51.66	55.45
Al ₂ O3	5.03	12.28	18.90	15.88
Fe ₂ O3	3.30	6.23	8.68	11.22
CaO	62.52	5.00	12.59	7.93
MgO	3.06	2.91	1.38	2.98
K ₂ O	0.60	1.23	0.98	1.17
Na ₂ O	0.26	0.04	0.01	0.04
SO ₃	2.54	0.26	1.13	0.02
Loss on Ignition	2.74	5.55	9.38	5.75

3.2.1.6.3 Microstructural and Physical Properties: Density, Surface Area, and Morphology

Microstructural and Morphological Evaluation Using Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) imaging was used to analyze the surface morphology, particle shape, and textural characteristics of the mineral additions, which significantly influence their hydration kinetics, dispersion in the cement matrix, and mechanical performance. SEM micrographs revealed that andesite particles exhibit a rough, angular surface texture, contributing to improved interlocking and mechanical bonding in HPC formulations. Natural marl, prior to calcination, displayed smooth, rounded grains with a compact structure, limiting its initial reactivity. However, after calcination, the material underwent a significant transformation, with particles exhibiting a porous, fragmented structure, increasing their reactive surface area and pozzolanic activity. Natural pozzolan showed a highly porous morphology with irregular, rough-edged grains, confirming its high potential for water absorption and improved cement paste adhesion. The SEM analysis provided crucial insights into the textural modifications resulting from calcination and their impact on hydration reactions, packing density, and overall HPC performance, as illustrated in Figure 3.20, which compares the microstructural features of the raw and processed SCMs.





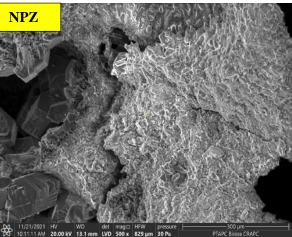


Figure 3.20: Scanning electron microscopy (SEM) images of natural marl (NM), andesite (AND), and natural pozzolan (NPZ) samples.

3.2.1.6.4 Physical Characterization of Mineral Additions:

The physical properties of the mineral additions—cement (C), andesite (AND), calcined marl (CM), and natural pozzolan (NPZ)—were evaluated through measurements of specific gravity and Blaine specific surface area.

The specific gravity values indicate that andesite (2.58 g/cm³) and natural pozzolan (2.57 g/cm³) have similar densities, suggesting good compatibility with cement in terms of mixture stability. Calcined marl exhibits a slightly higher specific gravity (2.64 g/cm³), while the reference cement shows a value of 3.12 g/cm³.

In terms of fineness, the Blaine specific surface area results reveal that andesite possesses the highest fineness (5856 cm²/g). Calcined marl and natural pozzolan also exhibit high fineness values, 5153 cm²/g and 5035 cm²/g respectively, supporting their effectiveness as supplementary cementitious materials (SCMs). The reference cement has a comparatively lower fineness of 3888 cm²/g.

These results, summarized in Table 3.2, confirm the physical suitability of the investigated mineral additions for use in high-performance concrete formulations.

Table 3.2: Physical properties of mineral additions.

Physical Properties	С	AND	CM	NPZ
Specific gravity (g/cm³)	3.12	2.58	2.64	2.57
Specific surface of Blaine (SSB) (cm²/g)	3888	5856	5153	5035

The comparative analysis presented in Table 3.3 highlights the chemical and physical properties of andesite (AND), calcined marl (CM), and natural pozzolan (NPZ) in relation to the standard requirements set by TS EN 450, TS EN 197-1, and ASTM C618-12. The compliance of these materials with established thresholds confirms their suitability as supplementary cementitious materials (SCMs) for high-performance concrete (HPC). Andesite, with a high combined SiO₂ + Al₂O₃ + Fe₂O₃ content of 84.06%, surpasses the minimum pozzolanic reactivity criteria (≥70%) and exhibits superior fineness (5856 cm²/g), enhancing C-S-H gel formation, which contributes to strength and durability. Calcined marl, while slightly lower in reactive silica (30%), meets pozzolanic standards and benefits from fine particle size (5153 cm²/g), improving workability and stability in cementitious systems. Natural pozzolan, with a balanced oxide

composition (SiO₂ + Al₂O₃ + Fe₂O₃ = 82.55%) and a fineness of 5035 cm²/g, demonstrates consistent pozzolanic behavior, facilitating matrix densification and long-term durability.

Additionally, the alkali content (K₂O and Na₂O) of these materials remains within acceptable limits, mitigating the risk of alkali-silica reaction (ASR), while SO₃ and Cl⁻ levels comply with sulfate and chloride restrictions, ensuring chemical stability in concrete formulations. The loss on ignition (LOI) values, ranging between 5.55% and 6.38%, align with permissible ranges, indicating controlled thermal processing. Table 3.3 further confirms that all three materials meet or exceed the specific requirements for Class F and Class C pozzolans, as defined by ASTM C618-12, reinforcing their viability as sustainable alternatives to conventional SCMs.

These findings emphasize the potential of utilizing locally sourced andesite, calcined marl, and natural pozzolan to enhance HPC performance while promoting environmentally responsible construction practices.

Table 3.3: Comparative Analysis of Mineral addition Properties Against Standard Specifications (TS EN 450, TS EN 197-1, ASTM C618-12).

Properties	Unit	AND	CM	NPZ	TS EN 450	TS EN 197-1	ASTM C 618-12	
							Class F	Class C
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	(%)	84.06	79.24	82.55	≥70		≥70	≥50
Reactive SiO ₂	(%)	40	30	45	≥25	≥25	_	_
SO ₃	(%)	0.26	1.13	0.02	≤3.0	_	≤5.0	≤5.0
K ₂ O	(%)	1.23	0.98	1.17	≤5.0 a	_	≤1.5 a	≤1.5 a
Na ₂ O	(%)	0.04	0.01	0.04				
MgO	(%)	2.91	1.38	2.98	≤4.0	_	_	_
Cl-	(%)	0.01	0.01	0.01	≤0.1	_	_	_
Free CaO	(%)	0	0	0	≤2.5	_		
Loss on Ignition	(%)	5.55	6.38	5.75	≤5-9	≤5.0	≤6	≤6
Retained on 45 m sieve	(%)				≤40	_	≤34	≤34
Specific gravity	(g/cm ³)	2.58	2.64	2.57	_	_	_	_
Fineness	(cm ² /g)	5856	5153	5035	-	-	-	-

a: The amount equivalent of alkaline substance (K₂O + 0.658 Na₂O).

3.2.1.7 Pozzolanic Reactivity Assessment of Andesite and Calcined Marl

3.2.1.7.1 Frattini Test: Evaluation of Calcium Hydroxide Consumption

The Frattini test, conducted in accordance with NF EN 196-5 [190], assesses the ability of pozzolanic materials to consume calcium hydroxide (CH) by measuring the Ca²⁺ and OH⁻ concentrations in a solution containing a mixture of 80% ordinary Portland cement (OPC) and 20% finely ground pozzolan. The prepared samples were maintained at 40°C for eight days, after which the filtrate was collected and analyzed for residual Ca²⁺ and OH⁻ ion concentrations. The degree of pozzolanic activity is determined based on the position of the test results relative to the solubility curve of calcium hydroxide.

The test begins by preparing a saturated calcium hydroxide solution, mixing 20.00 ± 0.01 g of cement with 100 mL of recently boiled distilled water in a sealed container. The solution is stirred for uniform dispersion and incubated at 40° C for eight days to establish equilibrium between dissolved Ca^{2+} and OH^{-} ions. If equilibrium is achieved at eight days, further incubation is unnecessary.

After incubation, the samples are filtered under vacuum within 30 seconds to prevent atmospheric CO_2 contamination. The filtrate's pH and hydroxide ion concentration ([OH⁻]) are determined through titration with standardized hydrochloric acid, while residual calcium oxide (CaO) concentration is measured using EDTA titration at an adjusted pH of 12.5 ± 0.2 . To ensure accuracy, all measurements are recorded to four decimal places, and the results are expressed in millimoles per liter (mmol/L), rounded to the nearest decimal place. Figure 3.21 illustrates the Frattini test preparation process, detailing key steps from sample collection to test setup.





Figure 3.21: Preparation Procedure for the Frattini Test.

Figure 3.22 illustrates the experimental setup used for hydroxide ion and calcium oxide concentration determination, highlighting key steps in the titration process.





Figure 3.22: Titration Procedure for Hydroxide Ion and Calcium Oxide Concentration Determination

The results, presented in Figure 3.23, indicate that both andesite and calcined marl exhibit significant pozzolanic reactivity, as their Ca²⁺ and OH⁻ concentrations fall below the lime solubility curve after the eight-day period. This behavior demonstrates that these materials effectively react with calcium hydroxide, forming additional cementitious compounds that contribute to improved concrete performance. The extended analysis at 15 days further confirmed this trend, indicating consistent and progressive pozzolanic behavior over time. These findings suggest that andesite and calcined marl can be integrated into cementitious systems to enhance hydration reactions and microstructural densification, making them viable alternatives to conventional SCMs [186].

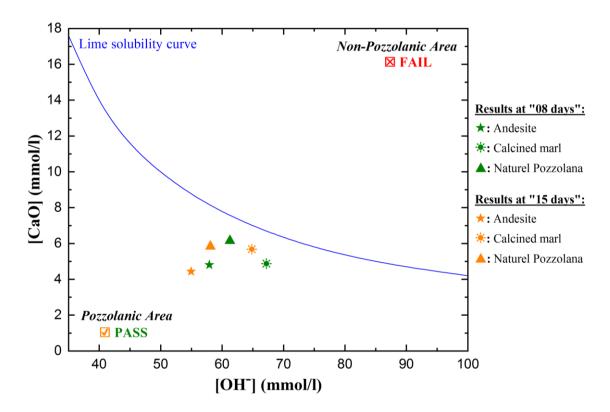


Figure 3.23: Frattini test results assessing the pozzolanic reactivity of andesite, calcined marl, and natural pozzolan.

3.2.1.7.2 Saturated Lime Test: Long-Term Lime Fixation Potential

In addition to the Frattini test, the saturated lime test was performed to evaluate the long-term pozzolanic reactivity of the tested materials. This test, widely used in pozzolanic research, involves reacting the SCM with a lime-saturated solution and monitoring the reduction in calcium ion concentration over time. In this study, a lime solution with a concentration of 2 g/L was prepared, and 1 g of pozzolan was mixed with 75 mL of this solution at 40°C [191]. The

amount of fixed calcium hydroxide was measured at 1, 3, 7, and 28 days to assess the rate and extent of pozzolanic activity [191].

The saturated lime test follows a simplified protocol derived from the Frattini test, in which a lime-saturated solution replaces cement as the reactive medium. To ensure accurate and reproducible results, all materials were analytical grade, and the procedure was conducted under controlled environmental conditions.

The preparation began with the preparation of the lime-saturated solution, where 2 grams of lime (aerial or hydraulic) were dissolved in 1 liter of distilled water to achieve saturation. The solution was then allowed to equilibrate before use. A precise 1 g mass of pozzolanic material was placed into a clean, dry polyethylene bottle, followed by the addition of 75 mL of the preprepared lime-saturated solution.

To facilitate the reaction and fixation of calcium hydroxide, the bottles were hermetically sealed and stored at 40°C for the designated reaction periods. The test setup ensured that the dissolution and precipitation equilibrium of calcium hydroxide was maintained throughout the experiment.

After each designated reaction period (1, 3, 7, and 28 days), the filtration and titration process was carried out. The solid and liquid phases were separated via vacuum filtration to remove any unreacted particles. The filtrate was then subjected to calcium ion titration using EDTA, a method that provides a precise measurement of the residual Ca²⁺ concentration in solution. The difference between the initial and residual Ca²⁺ content reflects the extent of lime fixation by the pozzolanic material.

To prevent errors, all volumetric and mass measurements were recorded to four decimal places, and the results were expressed in millimoles per liter (mmol/L) or as a percentage of lime reacted per gram of pozzolan. Figure 3.24 illustrates the preparation process of the saturated lime test, showing the key steps from solution preparation to sample incubation.





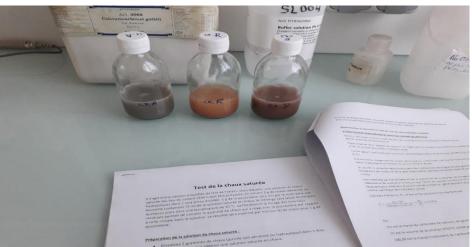




Figure 3.24: Preparation Procedure for the Saturated Lime Test.

Figure 3.25 illustrates the lime activity results, showing the extent of calcium hydroxide consumption by pozzolanic materials. The reaction is quantified by subtracting the residual Ca²⁺ ion concentration from the initial lime content. A higher lime fixation capacity signifies greater pozzolanic reactivity and improved cementitious properties.

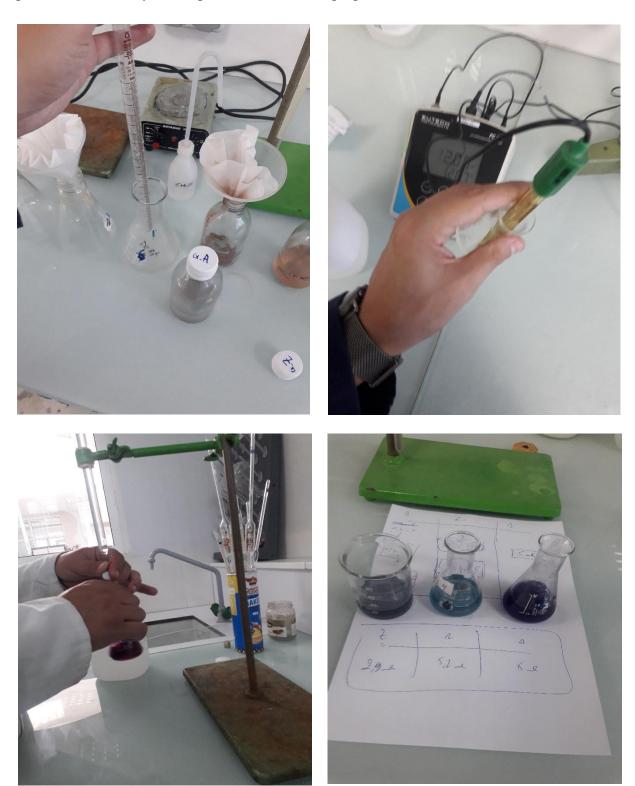


Figure 3.25: Determination of Calcium Hydroxide Reactivity in the Saturated Lime Test.

As illustrated in Figure 3.26, the findings reveal that andesite exhibited the greatest capacity for lime fixation, with a marked increase in reactivity between the 7th and 28th day, highlighting its pronounced pozzolanic activity. Calcined marl also demonstrated significant consumption of calcium hydroxide, albeit slightly lower than that of andesite, yet comparable to natural pozzolan, confirming its efficiency as a supplementary cementitious material. The sustained interaction of these materials with CH over an extended period underscores their potential for long-term durability, a critical factor in maintaining the stability and strength evolution of HPC mixtures [191].

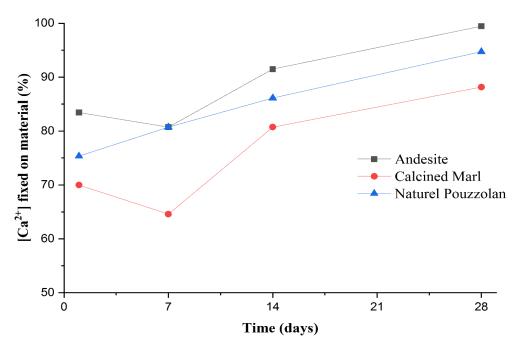


Figure 3.26: Long-term lime fixation potential of andesite, calcined marl, and natural pozzolan in the saturated lime test.

3.2.2 Aggregate and Chemical Admixtures Selection

The selection of aggregates and chemical admixtures plays a critical role in optimizing the workability, mechanical performance, and durability of high-performance concrete (HPC). Aggregates influence structural integrity, compactness, and permeability, while superplasticizers enhance fluidity, cohesion, and cement dispersion, ensuring an efficient cementitious matrix with reduced water demand.

3.2.2.1 Aggregate Characteristics and Particle Size Distribution

The aggregates used in this study include both fine and coarse fractions, all sourced from quarries in the Wilaya of Bordj Bou Arréridj. The combined use of well-graded fine and coarse aggregates is essential for achieving optimal packing density, reduced paste demand, and enhanced durability.

A granulometric analysis (Figure 3.27) confirmed that the fine aggregates (sand) contributed to improved cohesion and reduced segregation, while the coarse aggregates—comprising two size fractions, 3/8 mm and 8/15 mm gravel—provided enhanced interlocking, mechanical stability, and resistance to shrinkage. The overall grading curve aligns with particle packing models that aim to minimize voids and improve the fresh and hardened properties of HPC.

The physical characteristics of the coarse aggregates are presented in Table 3.4. The absolute densities of the 3/8 mm and 8/15 mm gravels were 2.73 g/cm³ and 2.74 g/cm³, respectively, indicating similar mineralogical composition. Both fractions showed consistent oven-dry bulk densities of 2.66 g/cm³ and saturated surface-dry densities of 2.69 g/cm³, reflecting low variability in porosity and good dimensional stability.

The flakiness index was measured at 11.57% for the 3/8 mm gravel and 8.35% for the 8/15 mm fraction, suggesting a predominance of regular-shaped particles favorable for compactness and mechanical performance. The Los Angeles abrasion value, assessed for the 8/15 mm gravel, was 23.78%, indicating good resistance to fragmentation. Its micro-Deval wear resistance was 16.9%, confirming its suitability for high-durability applications.

The mixing water, meeting NF P 18-404 standards [192], was potable, low in sulfates, and maintained at 20 ± 2 °C, ensuring no adverse effects on cement hydration

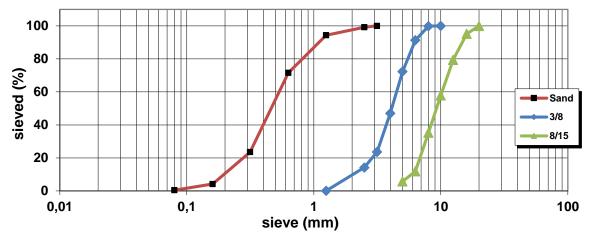


Figure 3.27: Granulometric Curves of Aggregates.

Table 3.4: Physical Properties of Gravel Aggregates

Physical Properties	3/8	8/15
Absolute Density (g/cm³)	2.73	2.74
Oven-Dry (Bulk) Density (g/cm³)	2.66	2.66
Saturated Surface-Dry Density (g/cm³)	2.69	2.69
Flakiness Index (%)	11.57	8.35
Los Angeles Abrasion Value (%)	/	23.78
Micro-Deval Wear Resistance (%)	/	16.9

3.2.2.2 Superplasticizer Selection and Dosage Optimization

To improve the workability and fluidity of the concrete mixtures while maintaining optimal cohesion and mechanical integrity, a polycarboxylate-based superplasticizer (SP), identified as MEDAFLOW 30, was incorporated into the mix. This high-range water-reducing admixture (HRWR) complies with the EN 934-2 standard [193] and was introduced into the concrete after 50–70% of the mixing water had been added. This sequencing ensures uniform dispersion of cement particles, enhancing the hydration process and reducing the risk of localized overdosage.

The use of MEDAFLOW 30 enables the production of a highly flowable and easily placeable concrete mix, achieving a low water-to-cement ratio without compromising stability. Its ability to efficiently disperse cement grains minimizes internal friction, reducing the need for excessive mechanical compaction while preventing segregation or excessive bleeding. By optimizing workability without increasing water demand, this admixture significantly contributes to the rheological performance of fresh concrete, ensuring enhanced homogeneity, improved pumpability, and better surface finish in HPC applications.

3.2.3 Optimization of High-Performance Concrete (HPC) Mix Design

3.2.3.1 Mix Proportioning Methodology

The development of high-performance concrete (HPC) formulations requires an optimized mix proportioning approach to achieve the desired balance between workability, mechanical performance, and durability. In this study, the mix design methodology is inspired by the

University of Sherbrooke approach, which integrates empirical optimization techniques with theoretical mix proportioning models. This method aligns with ACI 211.1-91 guidelines [194], [195], ensuring a systematic selection of concrete constituents to achieve maximum compactness, homogeneity, and durability.

The Sherbrooke method follows a structured approach that progressively refines the aggregate packing density and binder composition. The procedure begins with binary aggregate combinations, followed by ternary, quaternary, and ultimately pentagonal mixes, to maximize particle packing efficiency and minimize voids. The pentagonal aggregate blend has been demonstrated to provide the highest density and mechanical stability, which is crucial for ensuring long-term durability and high strength in HPC applications.

Additionally, this methodology incorporates the absolute volume method, which considers the volumetric contributions of cement, aggregates, admixtures, and water to optimize the final concrete mixture. By minimizing the paste volume while maintaining adequate workability, this approach enhances mechanical strength while reducing shrinkage and permeability, key factors for high-performance structural applications.

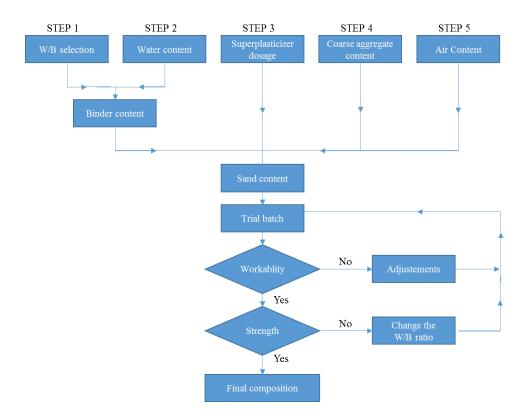


Figure 3.28: Schematic representation of the proposed mix design methodology [31].

3.2.3.2 Determination of Superplasticizer Dosage for Optimal Workability

The high-range water-reducing admixture (HRWR) used in this study was MEDAFLOW 30, a polycarboxylate-ether-based superplasticizer, selected for its high dispersing efficiency and compatibility with low water-to-binder ratio systems typically employed in high-performance concrete (HPC). The initial estimation of the superplasticizer dosage was based on recommendations from the technical data sheet and supported by findings from relevant literature and prior experimental studies involving HPC mixtures with comparable binder compositions and performance targets.

Although the technical data sheet of MEDAFLOW 30 specifies a recommended dosage range of 0.5% to 2.0% by weight of binder (in liquid form), the dosage adopted in this study was calculated based on the active solid content of the admixture. Taking into account the product's density and dry extract percentage, the effective dosage corresponds to 3.7% by weight of binder, when expressed as the total liquid volume required to provide the necessary quantity of active material.

This adjustment ensures that the actual polycarboxylate content aligns with the performance needs of the mix design. The selected dosage was experimentally validated through slump flow tests, which confirmed that the fresh concrete exhibited the required flowability, cohesiveness, and resistance to segregation. These results demonstrate that the applied dosage was necessary to achieve the target workability under the specific conditions of the studied HPC formulation.

3.2.3.3 Proportions of Optimized HPC Mixes

The reference high-performance concrete (HPC) formulation was designed with an initial cement content of 519 kg/m³, selected to meet the mechanical and durability performance criteria typically required for HPC. To evaluate the effect of supplementary cementitious materials (SCMs), partial cement replacement was carried out at levels of 10%, 20%, and 30% by mass, using andesite, calcined marl, and natural pozzolan.

Since these mineral additions have different absolute densities compared to cement, their incorporation required precise adjustments to ensure a constant binder volume. The corresponding quantities of each component were calculated using established volumetric conversion formulas, which account for material density and substitution ratio. These formulas were applied using input values—such as absolute density and, where applicable, dry matter content—obtained from the respective technical data sheets. This methodology allowed for

accurate determination of the mass of each material, ensuring volumetric equivalence across all binder formulations and consistent fresh-state behavior.

All mixtures were prepared with a fixed water-to-binder (W/B) ratio of 0.27, which was maintained throughout the experimental program to support the development of a dense matrix and allow for consistent comparison of SCM effects. The detailed mix compositions, including adjusted quantities of cement, SCMs, aggregates, water, and superplasticizer, are presented in Table 3.5, which illustrates the precision and consistency applied in the design of all HPC formulations.

Table 3.5: Mix proportions of high-performance concrete (HPC) per cubic meter (W/B ratio = 0.27).

Materials (kg)	10%	20%	30%
Water	117.00	117.00	117.00
Cement	467.00	415.00	363.00
supplementary cementitious materials (SCMs)	46.67	83.00	109.00
Gravel (03/08)	518.50	518.50	518.50
Gravel (08/15)	518.50	518.50	518.50
Sand (S)	695.46	702.00	719.00
Superplasticizer (SP)	19.38	19.38	19.38

3.2.4 Casting, Curing, and Heat Treatment Protocol

The casting, curing, and heat treatment procedures are essential for ensuring the homogeneity, mechanical integrity, and durability of high-performance concrete (HPC). This section outlines the standardized mixing process, specimen preparation, and the controlled heat-treatment cycle, which simulates industrial precast curing conditions, in accordance with EN 13369 standards [196].

3.2.4.1 Standardized Mixing Procedure

3.2.4.1.1 Mixing Sequence and Homogenization Steps

The HPC mixtures were prepared using a laboratory mechanical mixer, with all materials weighed precisely to maintain consistency. Initially, cement, mineral additions, and aggregates

were dry-mixed for one minute to achieve uniform distribution. Following this, 60% of the total mixing water was added, and the blend was mixed for another minute to initiate early hydration. The remaining 40% of the mixing water, pre-dissolved with MEDAFLOW 30 superplasticizer, was gradually introduced over 30 seconds to enhance dispersion. The final mixing phase lasted 1.5 minutes, completing a four-minute total mixing cycle, ensuring a homogeneous and well-dispersed concrete mix.





Figure 3.29: Laboratory Mechanical Mixing Process for HPC Preparation.

3.2.4.1.2 Quality Control Measures for Batch Consistency

To ensure the consistency and uniformity of concrete production throughout the experimental program, key fresh-state control tests were carried out before casting each batch. Specifically, the slump test was performed using the Abrams cone, in accordance with standardized procedures to assess the workability of the mixtures. This method provided a reliable and rapid indicator of any variation in water content, admixture efficiency, or mixing quality. In parallel, the fresh concrete density was measured to verify the homogeneity and stability of the mix.





Figure 3.30: Slump Test for Assessing Workability of HPC.

3.2.4.2 Specimen Preparation and Casting Process

3.2.4.2.1 Molding and Consolidation Techniques

The fresh concrete was poured into 100 mm cubic molds, ensuring uniform distribution. Vibration compaction was applied using a manual vibrator to eliminate air voids and improve density and structural integrity. The vibration process was stopped once a smooth surface free of air bubbles was achieved, indicating optimal consolidation.



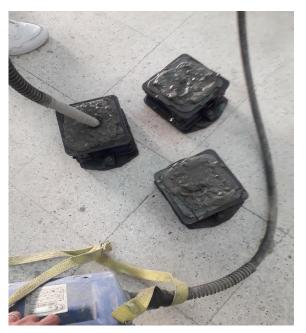




Figure 3.31: Molded and Consolidated HPC Specimens After Vibration Compaction.

3.2.4.2.2 Curing Regimes – Moisture Control and Duration

After 24 hours of initial setting in molds under laboratory conditions, the specimens were demolded and fully submerged in a water curing tank at a controlled temperature. This method ensures continuous hydration, preventing moisture loss and promoting optimal strength development. Figure 3.32 illustrates the immersion curing process, which enhances microstructural densification and long-term durability of the HPC specimens.



Figure 3.32: Water Immersion Curing of HPC Specimens.

3.2.4.3 Heat Treatment Protocol for Accelerated Curing

Thermal curing is a well-established method for accelerating cement hydration and early-age strength development in cementitious materials. However, improper thermal treatment can cause detrimental effects such as reduced ultimate strength, increased porosity, and thermal cracking. The optimization of thermal profiles requires careful balance between accelerated hydration benefits and potential long-term performance impacts.

The thermal curing cycle, illustrated in Figure 3.33, followed a controlled heating process to accelerate hydration and strength development while minimizing thermal stress. The protocol consisted of:

- Pre-treatment phase (Stabilization): Specimens were initially stored at 20°C for 4 hours after demolding. This period allowed the concrete to continue its early hydration under ambient conditions, reducing the risk of microcracking caused by sudden thermal gradients.
- Heating phase (Ramp-Up): The temperature was then gradually increased at a rate of 10°C per hour until reaching the target temperature of 60°C. This slow ramp-up minimized internal thermal stresses and ensured uniform heat distribution within the specimen.
- Isothermal phase (Heat Soaking): The temperature was held constant at 60°C for 16 hours. This isothermal plateau facilitated accelerated hydration of both Portland cement and supplementary cementitious materials, enhancing the early strength and densifying the microstructure.
- Cooling phase (Controlled Descent): Finally, the specimens were gradually cooled back to ambient temperature over approximately 2.5 hours, allowing thermal equilibrium to be restored without inducing shrinkage cracks or differential stress within the matrix.

This heat treatment protocol was designed to replicate real-world precast or industrial curing conditions where early demolding and rapid strength gain are critical, while also avoiding the adverse effects associated with excessive or uncontrolled thermal exposure.

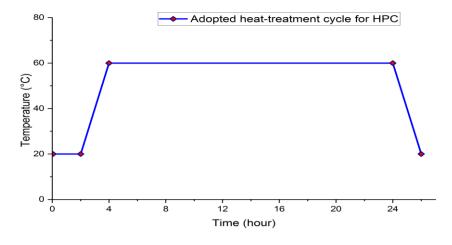


Figure 3.33: Applied heat-treatment cycle for high-performance concrete (HPC).



Figure 3.34: Heat Treatment Chamber for Accelerated Curing of HPC Specimens.

3.3 Characterization of HPC in Fresh and Hardened States

3.3.1 Fresh State Characterization

3.3.1.1 Slump Test and Workability Evaluation

The workability and consistency of the high-performance concrete (HPC) mixtures were evaluated using the slump test, conducted in accordance with the NF EN 12350-2:2019 standard [197]. This widely used method assesses the deformability of fresh concrete by measuring the vertical slump of the mix after removal of a standardized Abrams cone. It provides a reliable indication of the concrete's capacity to be placed and compacted without segregation or loss of cohesion.

The test was performed systematically on each batch to ensure consistency in fresh-state properties and to verify that the mixtures met the workability requirements defined for HPC applications. The results also served as a quality control measure, allowing for early detection of any deviations in water content, admixture dosage, or mixing procedure.

3.3.1.2 Absolute density measurements

The absolute density of the fresh concrete was measured using the gravimetric method, in accordance with the standard NF EN 12350-6:2019 [198]. This method consists of determining the absolute density of fresh concrete by calculating the ratio between the mass of a representative sample and the known volume of the container used. The test was performed immediately after mixing to ensure that the measurements reflected the actual composition and workability conditions of each batch. The container was first weighed empty, then filled with fresh concrete in layers while applying adequate consolidation—either by rodding or light vibration—to eliminate trapped air without inducing segregation. After leveling the surface, the filled container was weighed again, and the net mass of the concrete was obtained by subtracting the mass of the empty container. The internal volume of the container, known or previously calibrated using water, allowed the calculation of the density in kg/m³. This value was used to verify batch consistency and to detect potential variations in air content, which can significantly influence the durability, compressive strength, and homogeneity of high-performance concrete. Monitoring this parameter across all formulations ensured the reliability of the fresh-state characteristics and provided a basis for indirect evaluation of entrained air when compared to theoretical density values.

3.3.2 Hardened State Mechanical Properties

3.3.2.1 Compressive Strength Development at Various Curing Ages

The compressive strength of HPC was assessed at different curing ages, including 1, 7, 28, and 90 days, following the EN 12390-3 standard [199]. Compressive strength testing provides essential data on the load-bearing capacity and structural reliability of concrete, offering a comparative analysis of curing effects and material optimization. Standardized test specimens were used to ensure repeatability and accuracy in evaluating strength progression over time.

3.3.2.2 Ultrasonic Pulse Velocity (UPV) and Internal Homogeneity

To assess the internal quality and homogeneity of the hardened high-performance concrete (HPC), ultrasonic pulse velocity (UPV) tests were performed at 28 days in accordance with the NF EN 12504-4:2021 standard [200]. This non-destructive testing method consists of

transmitting high-frequency ultrasonic waves through the concrete to determine the velocity of wave propagation, which reflects the compactness and continuity of the internal matrix.

According to the standard, the UPV test enables the detection of internal flaws, voids, or microcracks, and allows for the evaluation of material uniformity and relative quality across different specimens. The principle is based on the fact that ultrasonic waves travel more rapidly through dense and homogeneous materials and are slowed down in the presence of pores, cracks, or heterogeneities. The test was conducted using a direct transmission configuration, where the transmitting and receiving transducers were placed on opposite faces of the specimen to ensure full path coverage.

The UPV values obtained provided a quantitative indication of the material integrity and helped to verify that the curing process and mix design led to a well-compacted, durable concrete.

3.3.3 Durability Performance and Microstructural Investigations

3.3.3.1 Porosity (P) and Water Absorption Capacity (WAC)

The porosity (P) and water absorption capacity (WAC) of hardened high-performance concrete (HPC) were evaluated at 28 days, based on procedures aligned with the principles described in the NF EN 12390 standard concerning hardened concrete testing [201]. These tests aim to characterize the volume of interconnected pores accessible to water and the material's ability to absorb and retain moisture—critical indicators of durability, permeability, and resistance to environmental degradation.

The testing protocol involved drying concrete specimens in an oven at 105 ± 5 °C until constant mass was reached, followed by immersion in water for a specified period. After saturation, the specimens were surface-dried and weighed. The difference between the saturated and dry mass was used to calculate the amount of absorbed water. This value was then related to the volume and dry mass of the specimen to determine the open porosity and water absorption capacity, respectively. These parameters provide essential insights into the internal structure and fluid transport characteristics of HPC, supporting the overall assessment of its long-term performance.

3.3.3.2 Resistance to Sulfuric Acid Attack

The chemical durability of HPC was assessed by exposing specimens to controlled sulfuric acid solutions, in accordance with ASTM C-1012[202]. This procedure simulates acidic environmental conditions, monitoring the physical and chemical resistance of HPC to aggressive degradation processes. The evaluation includes observing mass loss, surface

integrity, and microstructural changes, ensuring that the concrete meets performance requirements for chemical resistance in specialized applications.

Figure 3.35 illustrates the preparation of HPC specimens for sulfuric acid resistance testing. Specimens were carefully immersed in a controlled sulfuric acid solution, following ASTM C1012 guidelines [202], to simulate real-world acidic exposure. The setup ensures uniform acid contact, allowing for accurate assessment of physical and chemical deterioration over time. Regular monitoring was conducted to track changes in mass, surface integrity, and microstructural stability, providing critical insights into the durability performance of the concrete under aggressive conditions.









Figure 3.35: Immersion Setup for Sulfuric Acid Resistance Testing of HPC Specimens.

3.3.3.3 Microstructural Analysis via X-Ray Tomography

To gain insights into the internal structure of HPC, X-ray tomography imaging was conducted, offering a high-resolution, three-dimensional visualization of the concrete's microstructure. This technique enables the identification of voids, microcracks, and aggregate distribution, providing critical information on the compactness and phase interactions within the material. The use of X-ray tomography enhances the understanding of HPC's microstructural behavior, particularly regarding the influence of mineral additions and thermal curing on structural integrity.

3.4 Experimental Design and Statistical Analysis

To systematically evaluate the impact of Mineral Additions and heat treatment on high-performance concrete (HPC) performance, a Design of Experiments (DOE) approach was implemented. This statistical methodology enables a structured investigation of multiple factors, allowing for a data-driven optimization of mix formulations and curing conditions.

3.4.1 Factorial Experimental Design and Variable Selection

A factorial experimental design was adopted to analyze the interactions between key parameters affecting HPC properties. The study focused on:

- Mineral additions type and percentage, considering andesite (AND), calcined marl (CM), and natural pozzolan (NPZ).
- Curing conditions, including heat treatment and ambient curing.
- Compressive strength development at multiple curing ages to assess the evolution of mechanical properties.

By systematically varying these factors, the experimental design ensures a comprehensive assessment of both individual and combined effects, enabling the identification of optimal mix formulations and curing strategies.

3.4.2 Implementation of Design of Experiments (DOE) Methodology

The DOE methodology was applied to efficiently structure and interpret the experimental trials, ensuring that each test condition contributes to a robust statistical model. This method facilitates:

• Optimization of material combinations for enhanced mechanical and durability properties.

- Reduction of experimental variability by establishing a controlled framework for testing.
- Identification of significant factors influencing HPC performance, aiding in the selection of ideal mix proportions.

The structured approach of DOE enhances the efficiency and reliability of the experimental process, ensuring that valuable insights are obtained with minimal resource expenditure.

3.4.3 Regression Modeling and Response Surface Optimization

To establish quantitative relationships between key parameters and concrete performance, regression models were developed. These models provide:

- A predictive framework to estimate HPC properties based on mix composition and curing conditions.
- Mathematical formulations describing the influence of Mineral additions content and heat treatment on strength evolution.
- Response surface analysis to explore the optimal conditions for achieving superior mechanical properties.

This statistical modeling approach enables data-driven decision-making, allowing for precise optimization of HPC formulations based on predictive analysis rather than trial-and-error experimentation.

3.4.4 Factorial Design Configuration in JMP

The factorial experimental design was structured using JMP® statistical software to investigate the influence of mineral addition content and curing temperature on the compressive strength of high-performance concrete (HPC). The study considered three types of mineral additions—andesite (AND), calcined marl (CM), and natural pozzolan (NPZ)—each tested at 10%, 20%, and 30% replacement levels by mass of cement. Two curing temperatures were applied: $25\,^{\circ}$ C (ambient) and $60\,^{\circ}$ C (heat treatment). This resulted in a 3×2 full factorial design, applied separately to each mineral addition.

The response variable was the compressive strength, evaluated at both 28 and 60 days. This configuration enabled the assessment of both main effects and interaction effects between dosage and curing temperature, while also capturing strength evolution over time.

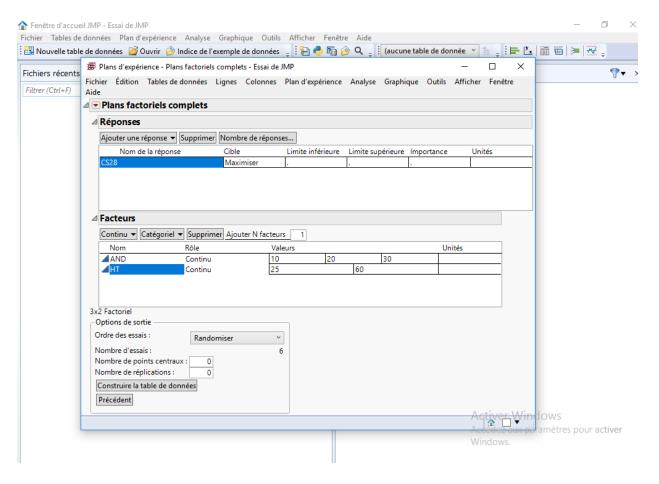


Figure 3.36: Factorial design configuration in JMP for high-performance concrete (HPC) optimization.

RESULTS & **DESCUSSION**

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CHAPTER 4:

RESULTS AND DISCUSSION

4 RESULTS AND DISCUSSION

4.1 Fresh State Properties of HPC

This section presents an analysis of the workability and density characteristics of high-performance concrete (HPC) incorporating andesite (AND), calcined marl (CM), and natural pozzolan (NPZ). The influence of Mineral additions content and superplasticizer dosage on the HPC mixtures.

4.1.1 Slump Test and Workability Assessment

4.1.1.1 Slump Test Trends and Influence of Mineral Additions

The workability of HPC mixtures is a crucial parameter in ensuring proper placement, compaction, and overall performance. The slump test with the Abrams cone, as illustrated in Figure 4.1, was conducted to assess the consistency of the fresh concrete mixtures. This test primarily assesses the vertical deformation of concrete under its own weight after demolding, offering a practical indication of the mixture's workability and cohesiveness. The measured slump values reflect the combined influence of water-to-binder ratio, superplasticizer dosage, and Mineral additions properties on the fresh state behavior of HPC. The images presented in Figure 4.1 visually capture the slump behavior of the concrete, illustrating its consistency after removing the mold.





Figure 4.1: Visual Representation of Slump Test for HPC Mixtures.

Figure 4.2 presents the results of the slump test performed on HPC mixtures incorporating varying proportions (10%, 20%, and 30%) of andesite (AND), calcined marl (CM), and natural pozzolan (NPZ). All mixtures demonstrated slump values between 20 and 25 cm, indicating a plastic and workable consistency suitable for high-performance concrete, with no signs of excessive segregation or bleeding.

A comparative analysis of slump trends reveals distinct behaviors based on the type and dosage of the mineral addition:

- Andesite-based HPC (AND-HPC) demonstrated relatively stable workability across all replacement percentages, with slump values remaining consistent around 21-23 cm. The slight variation observed suggests that andesite particles maintain adequate dispersion characteristics, likely due to their moderate reactivity and particle size distribution that does not significantly impair the paste's lubricating properties.
- Calcined marl-based HPC (CM-HPC) maintained excellent workability across all replacement levels (22-23 cm slump), indicating optimal particle packing and moderate reactivity that preserves flowability despite the typically high water demand of calcined material.
- Natural pozzolan-based HPC (NPZ-HPC) showed a slight decrease as the replacement level increased from 10% to 30%. This reduction can be attributed to the higher water absorption capacity and fine particle nature of natural pozzolan, which slightly reduces the free water available in the mix.

Overall, the relatively small differences in slump between the various mineral additions and dosages suggest that all three materials are compatible with HPC applications, provided the mix design is carefully optimized.

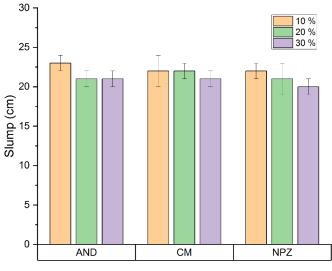


Figure 4.2: Slump measurements of HPC mixes containing different proportions of Mineral additions (AND: Andesite, CM: Calcined Marl, NPZ: Natural Pozzolan).

4.1.1.2 Superplasticizer Interaction with Mineral additions

The use of the polycarboxylate-based superplasticizer MEDAFLOW 30 was essential for ensuring adequate workability across all HPC mixtures. The interaction between the superplasticizer and the various supplementary cementitious materials (SCMs) revealed distinct behavioral trends:

- Mixtures containing andesite and calcined marl exhibited relatively stable slump values across all substitution levels, indicating that MEDAFLOW 30 was effective in dispersing particles and maintaining consistency, even at higher replacement rates. The slightly reduced sensitivity of andesite-based mixes suggests lower interaction with the admixture due to its moderate surface activity. Conversely, CM's finer texture and higher reactivity may have required greater dispersion efficiency, which the superplasticizer successfully provided.
- For NPZ-based mixtures, a modest decrease in slump was observed with increasing dosage, likely due to the higher absorption capacity of natural pozzolan. Nevertheless, MEDAFLOW 30 maintained acceptable plasticity across all NPZ levels, reflecting its adaptability to varying particle characteristics.

These observations underscore the importance of tailoring superplasticizer dosage according to the physical and chemical properties of each mineral addition to ensure consistent performance in HPC formulations.

4.1.2 Absolute Density and Homogeneity

4.1.2.1 Effect of SCM Content on Fresh Mix Density

The absolute density of fresh HPC mixtures, shown in Figure 4.3, remained within a range of 2500 to 2600 kg/m³, indicating that the inclusion of Mineral Additions did not significantly alter bulk density. However, subtle trends were observed:

 Andesite-based mixtures (AND-HPC) exhibited a progressive decrease in density with increasing substitution levels. Given the lower specific gravity of andesite (2.58 g/cm³), replacing a portion of the denser cement led to a measurable reduction in the mix's absolute density, especially at 30% replacement.

Calcined marl-based mixtures (CM-HPC) also demonstrated a slight reduction in fresh
density, consistent with its intermediate specific gravity (2.64 g/cm³). The relatively
high surface area of calcined marl may also contribute to increased air entrapment or
reduced paste compaction, reinforcing this trend.

• Natural pozzolan-based mixtures (NPZ-HPC) showed the lowest density values, particularly at higher replacement levels. This outcome aligns with the low specific gravity of NPZ (2.57 g/cm³), which is the lowest among the SCMs used. Despite this, the reduction in density remained within acceptable margins for HPC formulations.

In summary, the observed variation in fresh density reflects the direct influence of specific gravity differences between cement and each mineral addition. Nevertheless, all mixtures maintained densities suitable for high-performance concrete, confirming the feasibility of incorporating these SCMs without compromising mass balance or structural integrity.

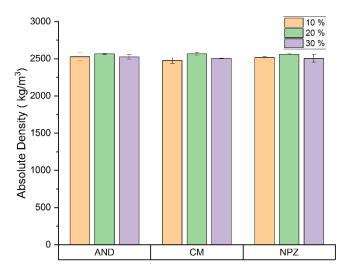


Figure 4.3: Absolute density of HPC mixes incorporating varying proportions of Mineral Additions (AND: Andesite, CM: Calcined Marl, NPZ: Natural Pozzolan).

4.1.2.2 Air Entrapment and Homogeneity Considerations

The inclusion of mineral additions slightly influenced air content and mix homogeneity. In general, superplasticizer use contributed to reducing entrapped air, promoting consistent density across mixtures. A modest increase in air content was noted with higher SCM dosages, particularly in CM-HPC mixtures, likely due to their finer particles and greater surface reactivity. In contrast, NPZ-HPC mixtures maintained stable densities, indicating limited impact on air entrapment and good dispersion within the cement matrix.

4.1.2.3 Relevance to Mix Design Optimization

The findings indicate that:

• Proper SCM selection and proportioning can maintain fresh mix density within optimal limits, supporting good cohesion and stability.

- The balance between particle packing efficiency and fluidity adjustments (via superplasticizer modifications) is crucial to avoiding excessive void formation.
- 10% to 20% SCM replacement appears optimal, ensuring good density retention and minimal air entrapment, while higher dosages (≥30%) require additional mix adjustments.

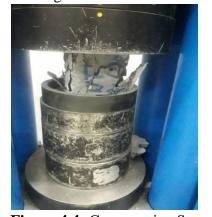
4.2 Hardened State Properties of HPC

This section presents the mechanical and durability characteristics of hardened high-performance concrete (HPC) mixtures. The detailed composition and test results for each formulation are provided in Table (Appendix 1).

4.2.1 Mechanical Performance of Hardened HPC

This section analyzes the compressive strength development of high-performance concrete (HPC) incorporating andesite (AND), calcined marl (CM), and natural pozzolan (NPZ). The influence of curing duration, heat treatment, and Mineral additions proportions is examined to understand the mechanical response of these mixtures in structural applications.

To assess the compressive strength of HPC, the specimens were subjected to testing using a universal testing machine (UTM) in accordance with standardized procedures. Figure 4.4 captures the failure of an HPC specimen under compressive loading, showcasing the fracture pattern and ultimate load-bearing capacity. The digital display of the testing machine provides a real-time record of the maximum applied force and corresponding compressive strength, offering a clear verification of the mechanical performance.



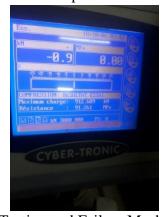


Figure 4.4: Compressive Strength Testing and Failure Mechanism of HPC Specimens.

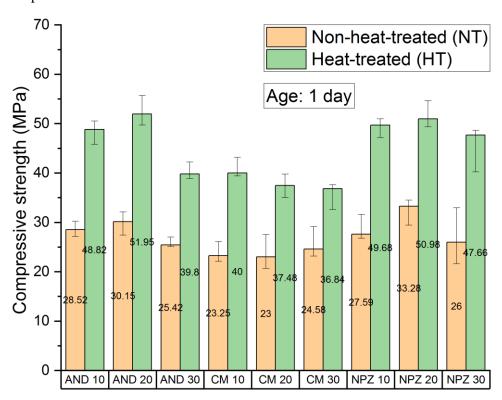
4.2.1.1 Compressive Strength Development at Different Curing Ages

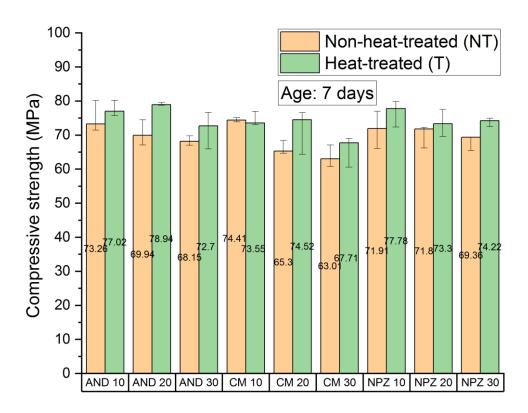
4.2.1.1.1 Strength Evolution Over Time

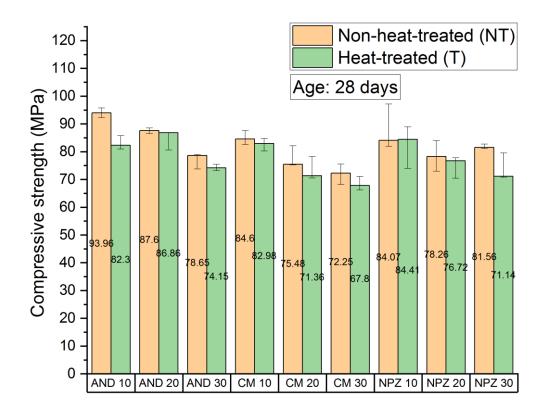
The compressive strength results at 1, 7, 28, and 60 days exhibit a clear trend of progressive strength gain, as expected in cementitious systems with supplementary cementitious materials (SCMs) [199]. Early-age strength development is primarily governed by hydration of Portland cement, while long-term strength benefits from the secondary pozzolanic reactions between SCMs and calcium hydroxide [13].

The compressive strength results for high-performance concrete (HPC) mixtures incorporating different SCMs over 1, 7, 28, and 60 days of curing are presented in Figure 4.5. These results provide a comparative analysis of the strength evolution for both heat-treated (HT) and non-heat-treated (NT) samples, illustrating the effects of Mineral additions type and replacement level on performance.

- At 1 day, a significant strength disparity is observed between HT and NT samples, with HT specimens reaching up to 52.44 MPa, whereas NT specimens range from 23.74 MPa to 32.40 MPa. This highlights the impact of accelerated hydration due to thermal curing [203].
- At 7 days, both NT and HT samples show a substantial increase in strength, with HT samples reaching 79.08 MPa and NT samples between 63.62 MPa and 74.95 MPa. The narrowing strength gap suggests that pozzolanic reactivity begins compensating for the initial lag in NT mixtures [204].
- By 28 days, NT samples attain their highest strengths, with some exceeding their HT counterparts, reflecting the progressive densification of the cementitious matrix via long-term hydration and pozzolanic activity. NT specimens exhibit strengths up to 94.01 MPa, while HT samples plateau at 84.79 MPa.
- At 60 days, NT mixtures maintain strength progression, peaking at 102.74 MPa, while HT mixtures reach 97.67 MPa. The continued increase in NT samples suggests enhanced pozzolanic activity and matrix refinement, surpassing the initial strength benefits of HT samples [13].







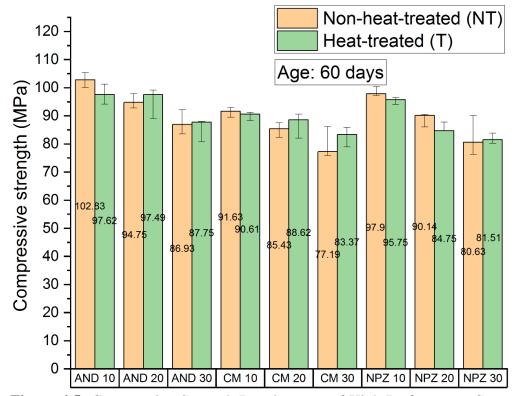
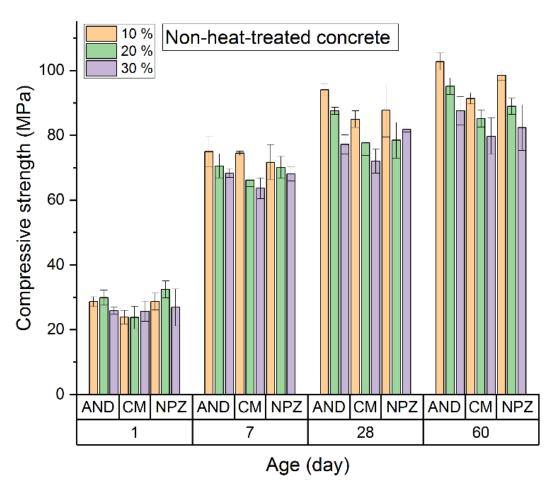


Figure 4.5: Compressive Strength Development of High-Performance Concrete (HPC) Over Various Curing Periods (1, 7, 28, and 60 Days) for Non-Heat-Treated (NT) and Heat-Treated (HT) Specimens.

4.2.1.1.2 Comparison Between Heat-Treated (HT) and Non-Heat-Treated (NT) Samples

The compressive strength results for HT and NT HPC mixtures at different curing ages are presented in Table 4.1 and Figures 4.6 and 4.7. The results demonstrate a notable strength advantage in HT specimens at early ages, but NT samples outperform HT mixtures at later ages, emphasizing the trade-off between early and long-term strength gain:

- HT mixtures: Show rapid strength development, beneficial for precast applications requiring early strength, but may experience slightly lower long-term gains due to reduced secondary hydration.
- NT mixtures: Benefit from continuous strength evolution, achieving higher long-term strengths due to enhanced pozzolanic activity. This makes NT curing suitable for structural applications prioritizing ultimate strength and durability.



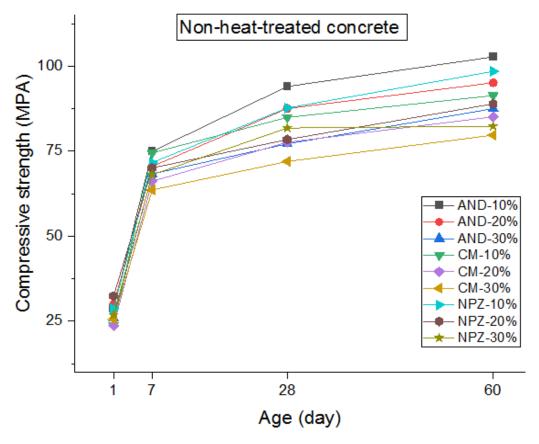
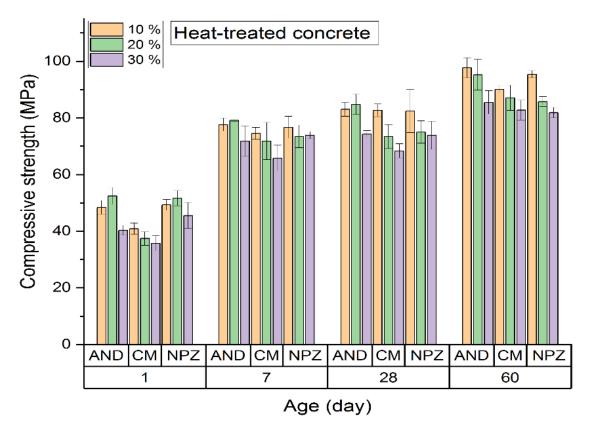


Figure 4.6: Evolution of Compressive Strength in Non-Heat-Treated Concrete Across Different Curing Ages (1, 7, 28, and 60 Days)



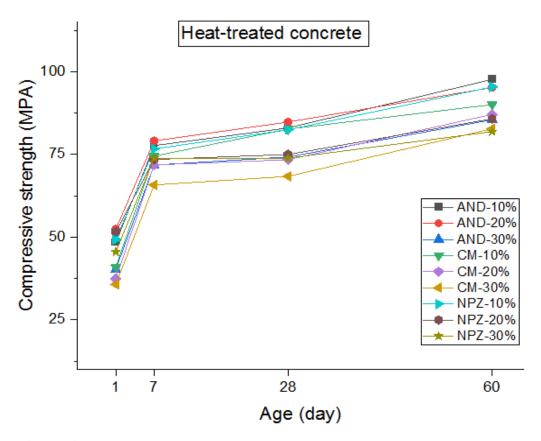
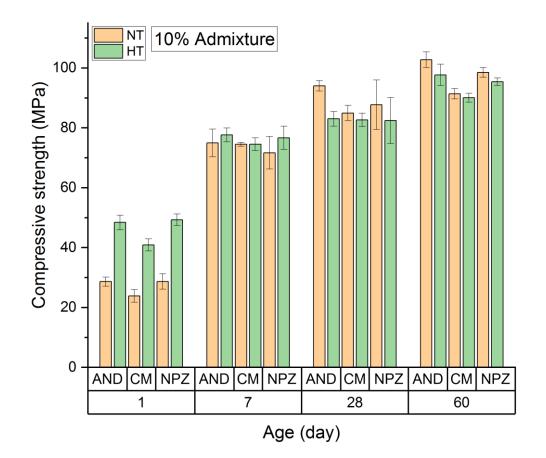


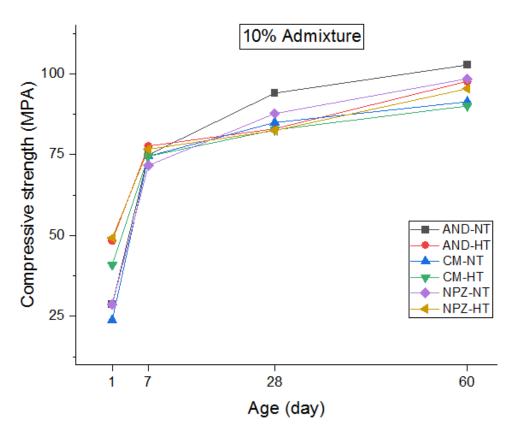
Figure 4.7: Evolution of Compressive Strength in Heat-Treated Concrete Across Different Curing Ages (1, 7, 28, and 60 Days).

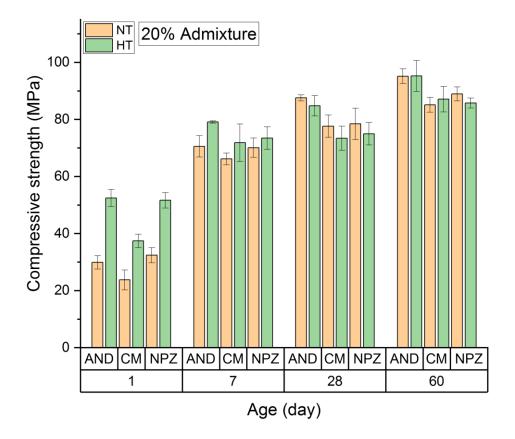
4.2.1.1.3 Impact of Mineral Additions Proportions

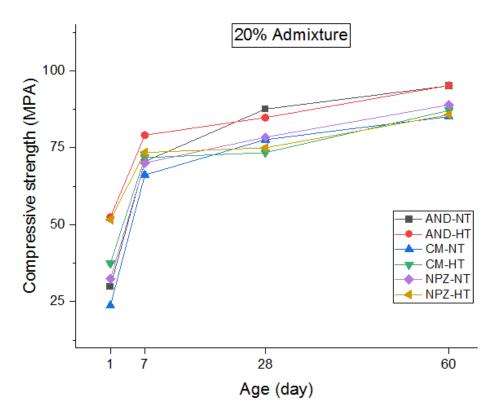
The substitution of cement with SCMs at 10%, 20%, and 30% levels influenced strength development across different curing durations. The effect of varying SCM dosages on compressive strength at different curing ages is illustrated in Figure 4.8.

- 10% substitution level: Exhibited the highest early-age strength under heat treatment, reaching up to 52.44 MPa at 1 day, making it ideal for rapid demolding applications.
- 20% substitution level: Showed a balanced strength progression, achieving 95.12 MPa at 60 days under NT conditions. This reflects an optimal balance between initial hydration and long-term pozzolanic reactions.
- 30% substitution level: Led to a reduction in overall strength, particularly in CM-based mixtures, where excessive replacement caused higher water demand and slower reaction rates [205].









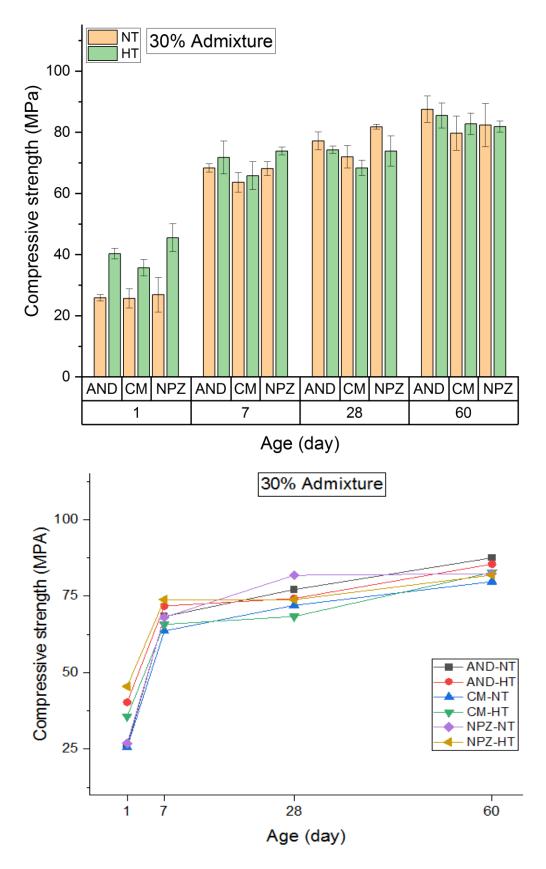


Figure 4.8: Compressive Strength of High-Performance Concrete (HPC) at Various Curing Durations for Non-Heat-Treated (NT) and Heat-Treated (HT) Specimens Incorporating Different Admixture Proportions (10%, 20%, and 30%).

4.2.1.2 Influence of Heat Treatment on Strength Evolution

4.2.1.2.1 Early-Age Strength Development

The 1-day strength values (Figure 4.5) confirm that heat treatment significantly enhances early compressive strength, with HT samples achieving up to 52.44 MPa, compared to 23.74 MPa to 32.4 MPa in NT specimens. This demonstrates the acceleration of hydration reactions due to elevated temperatures, which promote faster C-S-H gel formation and early matrix densification [203].

4.2.2.2 Hydration Kinetics Under Heat Curing

The reaction kinetics of cementitious phases under heat curing conditions are presented in Figures 4.6 and 4.7, where strength differences between HT and NT mixtures are compared over time. The data suggest that:

- Thermal curing accelerates hydration of clinker phases (C₃S and C₂S), enhancing early strength development [204].
- Pozzolanic activity is enhanced under heat treatment, particularly for andesite and natural pozzolan, which results in improved matrix compactness at early ages.
- Excessive heat curing can induce microstructural porosity, leading to slightly lower long-term strength compared to NT samples due to reduced secondary hydration contributions.

4.2.1.2.2 Long-Term Mechanical Stability

Figures 4.6 and 4.7 further illustrate that, despite initial advantages of heat curing, NT specimens continue to gain strength beyond 28 days, surpassing their HT counterparts at 60 days. This confirms that long-term hydration and pozzolanic activity in NT samples contribute to superior strength retention.

4.2.2 Effect of Mineral additions Dosage on Strength Performance

4.2.2.1 Strength Variations with Increasing SCM Levels

The influence of different SCM dosages on compressive strength over time is illustrated in Figure 4.8. The results confirm that moderate SCM dosages (10%-20%) enhance both early and long-term mechanical performance, whereas excessive SCM replacement (≥30%) can hinder strength efficiency due to:

• Increased water demand, leading to potential workability and compaction issues.

• Incomplete pozzolanic reactions, leaving unreacted mineral particles that reduce strength development.

4.2.2.1.1 Optimal Replacement Levels

Based on the findings illustrated in Figure 4.8, the best-performing SCM dosage varies depending on the curing regime and targeted application:

- For early-age strength (precast applications) → 10% SCM replacement under heat treatment is recommended.
- For structural applications requiring high durability → 20% SCM replacement under normal curing offers superior long-term strength development.
- For cost-efficient cement reduction → 30% SCM replacement may be feasible but requires optimized mix adjustments to mitigate strength loss.

4.2.2.1.2 Pozzolanic Reaction Contributions

The role of SCMs in enhancing compressive strength is primarily linked to their reactivity with calcium hydroxide (CH), forming additional C-S-H phases that densify the matrix [62].

- Andesite (AND): Provides moderate pozzolanic activity, enhancing early and long-term strength.
- Calcined Marl (CM): Exhibits high early reactivity, but excessive replacement may negatively impact long-term performance due to increased water demand.
- Natural Pozzolan (NPZ): Displays consistent pozzolanic contributions, ensuring progressive strength development over time.

4.2.3 Durability and Transport Properties

4.2.3.1 Porosity (P) and Water Absorption Capacity (WAC)

4.2.3.1.1 Determination of Total Porosity

Porosity and water absorption capacity (WAC) are key indicators of the durability and permeability of high-performance concrete (HPC), particularly in aggressive environmental conditions. As shown in Figure 4.9, the results obtained at 28 days for HPC mixtures incorporating andesite, calcined marl, and natural pozzolan at varying substitution levels reveal consistent trends.

The results indicate that moderate SCM incorporation (10% and 20%) leads to lower porosity, whereas higher substitution levels (30%) result in increased void content, which could negatively impact mechanical strength and long-term performance [204].

At 10% and 20% SCM replacement, the porosity values are notably low, particularly for andesite, which achieves 2.17% and 2.10%, respectively. These values are comparable to those of calcined marl and natural pozzolan, indicating that moderate levels of SCM improve packing density, reduce voids, and enhance matrix cohesion [203]. However, at 30% SCM replacement, the porosity increases significantly, reaching 2.57% in andesite-based HPC, which is the highest among all samples. This increase is attributed to the higher volume of mineral particles, which disrupts efficient packing and creates interconnected voids, leading to a less compact microstructure [204].

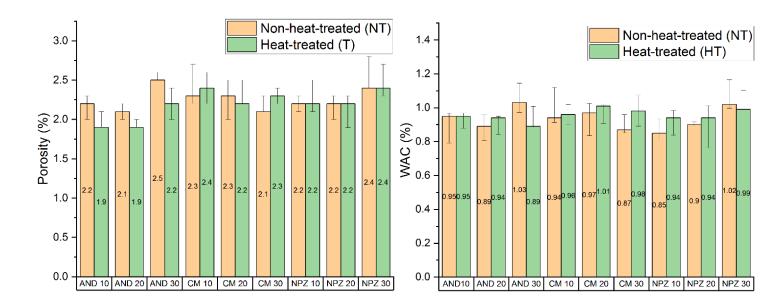


Figure 4.9: Total Porosity (P) and Water Absorption Capacity (WAC) of Non-Heat-Treated (NT) and Heat-Treated (HT) High-Performance Concrete (HPC) at 28 Days Incorporating Andesite (AND), Calcined Marl (CM), and Natural Pozzolan (NPZ).

4.2.3.1.2 Effect of SCM Content on Permeability

The influence of SCM content on water absorption and permeability follows a similar trend to porosity measurements, as shown in Figure 4.10.

• Lower SCM contents (10%-20%) reduce pore connectivity, leading to lower permeability and enhanced durability.

• At 30% SCM replacement, an increase in porosity correlates with higher water absorption capacity (WAC), suggesting that excessive SCM content may compromise long-term durability by creating microstructural discontinuities.

• Calcined marl (CM) performs better at high substitution levels, as its finer particle size enables better void filling, resulting in denser microstructures compared to andesite and natural pozzolan.

The WAC measurements confirm this behavior, where:

- Andesite-based HPC exhibits lower WAC values at 10% and 20% replacement, confirming its ability to enhance matrix densification and reduce permeability.
- At 30% replacement, WAC increases to 1.05%, indicating a higher capacity for moisture ingress, which could affect the durability of the structure over time.

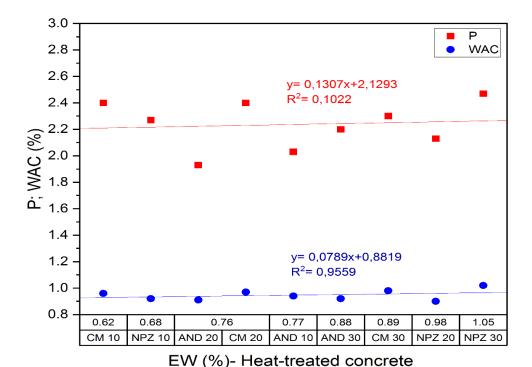


Figure 4.10: Correlation Between Porosity, Water Absorption Capacity, and Evaporated Water in Heat-Treated HPC, Considering SCM Type and Dosage.

4.2.3.1.3 Role of Heat Treatment in Minimizing Water Absorption

The effectiveness of heat treatment in reducing porosity and WAC is evident across all SCMs, though its impact varies based on material type and dosage. Figure 4.10 illustrates the decrease in porosity values after heat treatment:

• Andesite exhibits a significant porosity reduction, from 2.17% to 2.03% at 10% and from 2.57% to 2.20% at 30%, highlighting its responsiveness to thermal curing.

- Calcined marl remains relatively unaffected, with porosity values around 2.40% at 10% and a slight increase at higher substitution levels, indicating that its dense microstructure is achieved even without heat treatment.
- Natural pozzolan shows moderate improvement, with porosity decreasing from 2.53% to 2.47% at 30% after heat treatment, suggesting partial benefits from thermal activation.

A similar trend is observed in WAC values, where heat treatment results in:

- A decrease in WAC across all SCM types, with andesite reducing from 1.05% to 0.92% at 30% replacement, further confirming improved densification.
- Higher evaporated water (EW) in natural pozzolan-based HPC, leading to higher residual porosity and increased WAC.

4.2.3.1.4 Implications for HPC Durability

The correlation between porosity, WAC, and heat treatment effects suggests that:

- Optimal SCM levels (10%-20%) provide the best balance between strength, durability, and permeability resistance.
- Excessive SCM replacement (≥30%) may lead to increased porosity and water absorption, requiring additional mix design modifications to maintain performance.
- Heat treatment significantly enhances matrix densification, particularly in andesite-based HPC, by promoting early hydration and secondary C-S-H formation.
- Calcined marl exhibits naturally low porosity, making it less dependent on heat treatment for durability improvements.

These findings highlight the importance of optimizing SCM content and curing conditions to achieve high-performance, durable concrete for long-term structural applications.

4.2.3.2 Ultrasonic Pulse Velocity (UPV) and Microstructural Integrity

4.2.3.2.1 Non-Destructive Evaluation of Concrete Compactness

Ultrasonic Pulse Velocity (UPV) testing is a widely accepted non-destructive method for evaluating the internal compactness and homogeneity of concrete. This technique measures the velocity of high-frequency waves traveling through the hardened concrete. Higher UPV values

indicate a more continuous and compact internal structure, with fewer microcracks, voids, or defects—factors that contribute to improved durability and mechanical performance [206].

Following the UPV principles, Figure 4.11 presents the experimental setup used for ultrasonic pulse velocity testing, demonstrating the placement of transducers on the HPC specimens and the digital readout of wave transmission.

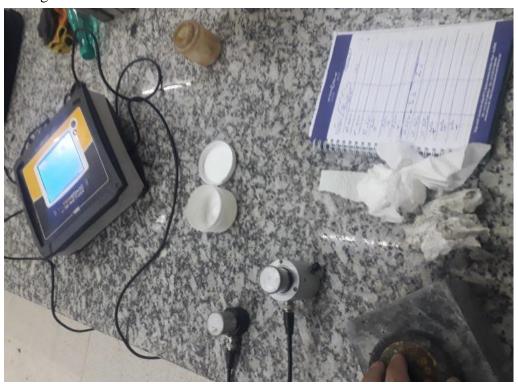


Figure 4.11: Ultrasonic Pulse Velocity (UPV) Testing for Concrete Compactness Evaluation.

The UPV measurements for different HPC mixtures are presented in Figure 4.12, comparing HT and NT samples. The results indicate that NT samples consistently exhibit higher UPV values, ranging from 4587.88 m/s to 4801.99 m/s, which suggests a denser and more homogeneous microstructure. In contrast, HT samples show slightly lower UPV values, ranging from 4459.55 m/s to 4725 m/s, indicating minor reductions in compactness due to heat treatment [207].

Despite the slight decline in UPV for HT mixtures, all samples maintain values above 4200 m/s, classifying them as high-quality concrete with good structural integrity and compactness [207].

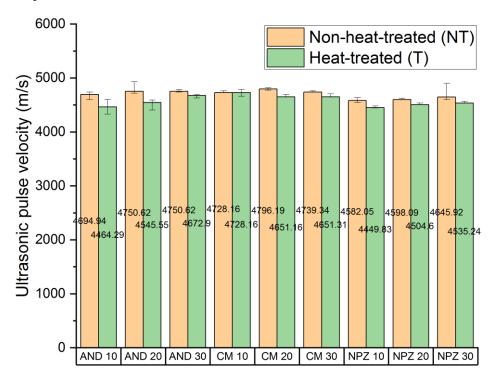


Figure 4.12: Ultrasonic Pulse Velocity (UPV) Measurements of Non-Heat-Treated (NT) and Heat-Treated (HT) HPC Mixtures at 28 Days, Highlighting Variations in Compactness and Homogeneity.

4.2.3.2.2 Comparison Between Heat-Treated and Standard-Cured Samples

The impact of heat treatment on microstructural integrity is evident in the UPV measurements. Although HT samples exhibit slightly lower UPV values, the difference remains within acceptable limits, indicating that:

- Heat treatment does not significantly compromise HPC compactness, as all samples exceed the 4200 m/s UPV threshold for high-quality concrete.
- NT samples consistently achieve superior compactness, suggesting that gradual hydration and secondary pozzolanic reactions contribute to enhanced densification over time.
- Minor reductions in UPV for HT specimens may be attributed to microcracking or increased internal porosity caused by rapid hydration and thermal expansion.

Overall, these findings confirm that both NT and HT HPC mixtures exhibit strong structural integrity, making them suitable for durable construction applications. The slight differences in UPV suggest that heat treatment should be carefully optimized to prevent potential microstructural disruptions.

4.2.3.3 Resistance to Sulfuric Acid Attack

4.2.3.3.1 Testing Methodology for Acid Resistance

To evaluate the acid resistance of HPC, concrete specimens were submerged in a sulfuric acid solution for a predetermined period, during which their mass loss and compressive strength degradation were systematically monitored. This method allows for the assessment of the durability of the HPC mixtures when exposed to aggressive chemical environments. The progression of surface deterioration and material degradation was visually examined to correlate physical changes with mechanical performance. Figure 4.13 presents the concrete specimens after immersion in the acid solution, illustrating the extent of deterioration and confirming the impact of prolonged exposure on HPC durability.







Figure 4.13: HPC Specimens After Immersion in Sulfuric Acid Solution.

The results, shown in Figures 4.14, 4.15, and 4.16, highlight progressive deterioration in compressive strength and mass loss across all tested mixtures.

After 60 days of sulfuric acid exposure, all HPC samples exhibited significant strength reductions, reflecting the degradative effects of acidic environments on the cementitious matrix. NT samples initially had higher compressive strength than HT samples but experienced greater strength losses post-exposure, suggesting that pozzolanic reactivity and microstructural characteristics influence acid resistance [208].

4.2.3.3.2 Impact of SCMs on Acid Resistance

The performance of different Mineral Additions in resisting sulfuric acid degradation varied based on substitution levels and curing conditions:

- Compressive Strength Loss: NT samples exhibited strength reductions between 39% and 52%, with HPC-10 CM showing the highest loss (52%) and HPC-10 AND exhibiting the least (39%). Conversely, HT samples displayed strength losses ranging from 38% to 48%, where HPC-10 AND performed best (38%), while HPC-20 AND recorded the highest reduction (48%).
- Comparative Performance of SCMs: While calcined marl (CM) mixtures generally suffered greater strength reductions, the overall differences between andesite (AND),

calcined marl (CM), and natural pozzolan (NPZ) were relatively minor, indicating that all three SCMs contribute similarly to acid resistance.

• Influence of Microstructural Quality: Mixtures characterized by lower total porosity and higher compactness — as indicated by UPV and fresh-state consistency — tended to perform better under acidic conditions. This reinforces the role of microstructural densification and pore refinement in limiting acid penetration and degradation.

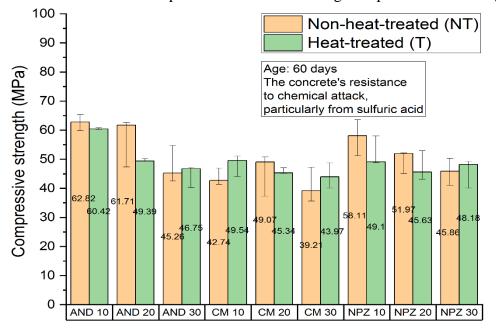


Figure 4.14: Compressive strength of HPC after 60 days in sulfuric acid for NT and HT samples with varied admixtures.

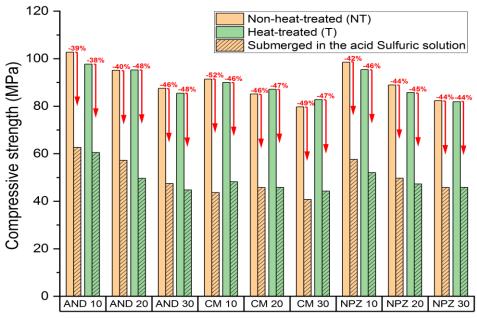


Figure 4.15: HPC compressive strength comparison in sulfuric acid vs. control, with strength loss percentage.

4.2.3.3.3 Surface Deterioration and Mass Loss Assessment

In addition to strength degradation, sulfuric acid exposure led to progressive mass loss, as summarized in Figure 4.16.

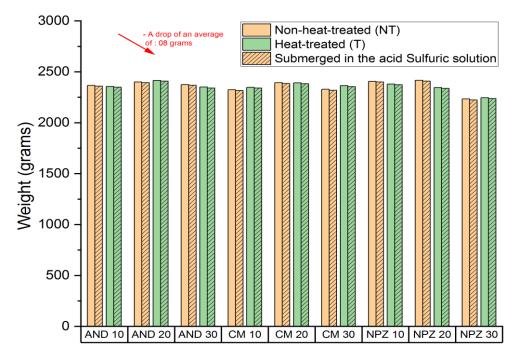


Figure 4.16: Assessment of weight variation in HPC specimens following sulfuric acid exposure, presenting initial, final, and net mass change (grams) for NT and HT mixtures.

Both HT and NT samples exhibited weight reductions between 6 and 10 grams, consistent with the dissolution and leaching of calcium compounds from the concrete matrix.

HPC mixtures with improved compactness, regardless of SCM type, exhibited lower weight losses, highlighting the role of microstructural refinement in enhancing chemical resistance.

The combination of compressive strength loss and mass change data suggests that while Mineral Additions improve early-age HPC properties, their long-term acid resistance remains relatively similar. Despite minor variations, all SCMs contributed to balanced performance, helping maintain residual strength and limiting excessive mass loss post-exposure.

4.2.4 Microstructural and Phase Characterization

4.2.4.1 Tomography Analysis of HPC Mixtures

4.2.4.1.1 Microstructural Visualization Techniques: Application of X-Ray Tomography for 3D Imaging

X-ray computed tomography (CT) scanning provides a non-destructive method for assessing the internal structure of HPC samples, enabling 3D visualization of microstructural attributes such as pore distribution, aggregate bonding, and ITZ quality [209]. The tomography images in Figure 4.17 illustrate the internal arrangement of mineral particles, microcrack propagation, and void content in HPC mixes containing AND, CM, and NPZ. The vertical arrangement of samples from bottom to top (CM, NPZ, AND) allows for direct comparison of microstructural differences among these SCMs [2].

4.2.4.1.2 Identification of Microcracks, Voids, and Aggregate Bonding

The analysis of ITZ and microcrack distribution reveals distinct differences in microstructural integrity among HPC mixtures:

- NPZ-based HPC exhibits a highly compact matrix with a dense, well-defined ITZ and
 minimal microcracking, indicating strong particle-paste interactions and enhanced crack
 resistance. The low porosity of the ITZ suggests optimal hydration and pozzolanic
 reactivity, which strengthens the cementitious matrix.
- Andesite-based HPC shows a moderately dense ITZ, with slightly wider transition zones compared to NPZ. While aggregate-paste bonding remains strong, some microcracks are present, though they are small and evenly distributed, suggesting good crack control and durability.
- Calcined marl (CM)-based HPC presents higher ITZ porosity, with a more heterogeneous distribution of particles. The presence of microcrack networks is slightly more pronounced, likely due to increased permeability and reduced particle-paste cohesion. These microstructural discontinuities may affect long-term durability, especially under mechanical and environmental stress.

4.2.4.1.3 Effect of SCMs on Interfacial Transition Zone (ITZ) Quality

The quality of the ITZ is a critical factor in HPC performance, influencing permeability, mechanical strength, and durability. The tomography analysis confirms that:

- NPZ enhances ITZ densification, leading to low permeability and improved resistance to microcracking, making it ideal for high-durability applications.
- Andesite-based HPC achieves a balance between strength and durability, with controlled microcracking and moderate ITZ porosity, allowing for efficient stress distribution within the matrix.
- Calcined marl results in slightly higher ITZ porosity, which may limit durability, though it still forms a cohesive structure suitable for HPC applications.

These findings confirm that SCMs significantly influence the microstructural characteristics of HPC, impacting mechanical performance, permeability, and long-term resilience.

4.2.4.2 Phase Distribution and Densification Mechanisms

4.2.4.2.1 Hydration Phase Evolution: Formation of C-S-H Gels and Secondary Reaction Products

The hydration process in HPC leads to the formation of calcium silicate hydrate (C-S-H) gels, which contribute to matrix densification and strength development. The tomography analysis highlights:

- NPZ promotes the most extensive C-S-H gel formation, leading to high matrix compactness and improved ITZ quality. This contributes to increased compressive strength and reduced permeability.
- Andesite-based HPC exhibits moderate hydration activity, with uniformly distributed
 C-S-H phases, ensuring consistent strength development and balanced porosity reduction.
- Calcined marl contributes to early hydration, but its higher porosity and heterogeneous
 phase distribution result in slightly lower densification efficiency compared to NPZ and
 andesite.

These variations emphasize that SCMs not only modify microstructural integrity but also affect hydration kinetics and secondary phase formation.

4.2.4.2.2 Role of SCMs in Microstructural Densification: Pozzolanic Reactions and Pore Refinement

The effectiveness of SCMs in densifying HPC microstructure is directly linked to pozzolanic reactions:

- NPZ contributes significantly to pore refinement, reducing capillary porosity and improving long-term strength retention.
- Andesite enhances matrix compaction, supporting good mechanical performance while maintaining manageable permeability.
- Calcined marl, despite slightly higher porosity, remains effective in bonding and overall structure consolidation, making it a viable SCM option.

These findings align with existing studies on pozzolanic activity and SCM performance, confirming that optimized SCM dosages contribute to improved concrete durability and performance.

4.2.4.2.3 Heat Treatment Effects on Phase Transformation: Changes in Material Crystallinity and Mineral Stability

The influence of heat treatment (HT) on phase transformation is evident in the tomography data, where:

- HT samples exhibit improved matrix densification at early ages, accelerating C-S-H gel formation and reducing initial porosity.
- However, long-term microstructural changes in HT samples suggest potential thermal-induced microcracking, particularly in calcined marl-based HPC.
- NPZ and andesite-based HPC maintain stable phase structures under HT conditions, ensuring consistent strength development and durability.

These results indicate that heat treatment should be optimized to maximize early strength gains while minimizing long-term microstructural damage.

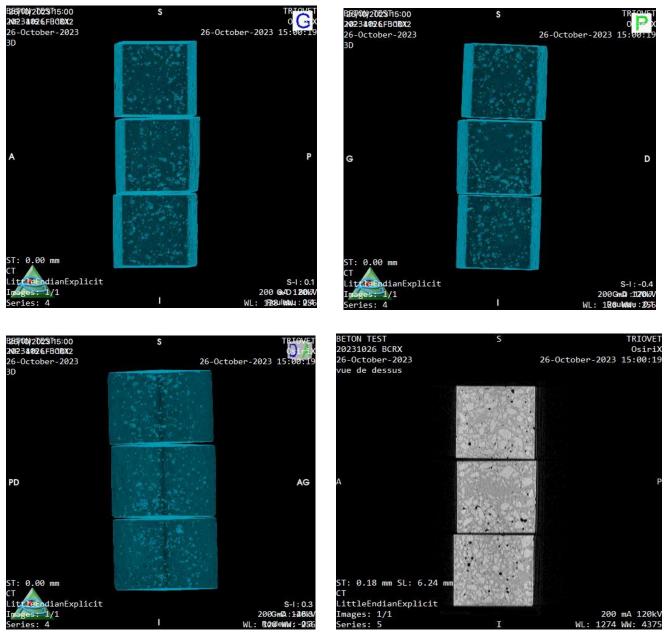


Figure 4.17: Tomographic imaging depicting microstructural variations in HPC mixtures incorporating calcined marl (CM), natural pozzolan (NPZ), and andesite (AND), with emphasis on ITZ integrity, porosity distribution, and crack propagation.

4.2.5 Statistical Modeling and Predictive Analysis

4.2.5.1 Factorial Design and Regression Analysis

4.2.5.1.1 Selection of Experimental Factors and Response Variables

A factorial design of experiments (DOE) was used to systematically investigate the influence of Mineral additions percentage (10%, 20%, and 30%) and heat treatment (NT: Non-Heat-

Treated, HT: Heat-Treated) on the compressive strength (CS) of HPC at 28 and 60 days. The factorial approach enables:

- Understanding the individual and interaction effects of SCM dosage and heat treatment.
- Optimizing mix design parameters to maximize compressive strength.
- Developing predictive regression equations linking SCM content, curing regime, and strength outcomes.

4.2.5.1.2 Development of Regression Models

The established regression models provide a means to estimate compressive strength as a function of heat treatment conditions and Mineral additions dosage. These mathematical formulations, derived from experimental data, enable the prediction of HPC performance at 28 and 60 days by capturing the influence of key variables. The resulting equations, expressed in a structured format, offer a quantitative representation of the strength evolution under different curing and material compositions. The predictive models are outlined as follows:

$$CS. AND \ (28 days) = 83.458 - 6.405 \cdot \left(\frac{(AND-20)}{10}\right) - 2.775 \cdot \left(\frac{(HT-42.5)}{17.5}\right) + 2.025 \cdot \left(\frac{(HT-42.5)}{17.5}\right) \cdot \left(\frac{(AND-20)}{10}\right) \tag{1}$$

$$CS. CM \ (28 days) = 76.483 - 6.815 \cdot \left(\frac{(CM - 20)}{10}\right) - 1.69 \cdot \left(\frac{(HT - 42.5)}{17.5}\right) - 0.34 \cdot \left(\frac{(HT - 42.5)}{17.5}\right) \cdot \left(\frac{(CM - 20)}{10}\right) \tag{2}$$

$$CS.NPZ\ (28days) = 79.868 - 3.625 \cdot \left(\frac{(NPZ-20)}{10}\right) - 2.782 \cdot \left(\frac{(HT-42.5)}{17.5}\right) - 0.675 \cdot \left(\frac{(HT-42.5)}{17.5}\right) \cdot \left(\frac{(NPZ-20)}{10}\right) \tag{3}$$

$$CS. \, AND \, \left(60 \, days\right) = 93.958 - 6.85 \cdot \left(\frac{(AND - 20)}{10}\right) - 1.172 \cdot \left(\frac{(HT - 42.5)}{17.5}\right) + 0.755 \cdot \left(\frac{(HT - 42.5)}{17.5}\right) \cdot \left(\frac{(AND - 20)}{10}\right) \tag{4}$$

$$CS. CM \ (60 days) = 86.012 - 4.73 \cdot \left(\frac{(CM - 20)}{10}\right) + 0.618 \cdot \left(\frac{(HT - 42.5)}{17.5}\right) + 1.09 \cdot \left(\frac{(HT - 42.5)}{17.5}\right) \cdot \left(\frac{(CM - 20)}{10}\right) \tag{5}$$

$$CS. NPZ \ (60 days) = 88.795 - 7.418 \cdot \left(\frac{(NPZ - 20)}{10}\right) - 1.128 \cdot \left(\frac{(HT - 42.5)}{17.5}\right) + 0.648 \cdot \left(\frac{(HT - 42.5)}{17.5}\right) \cdot \left(\frac{(NPZ - 20)}{10}\right) \tag{6}$$

The accuracy of these equations was assessed through coefficient of determination (R²) values, indicating strong predictive capability, with R² values close to 1.

4.2.5.1.3 Analysis of Variance (ANOVA) and Model Significance

ANOVA was performed to evaluate the statistical significance of the predictive models across different age periods and treatment conditions. The regression analysis revealed strong correlations between predicted and observed compressive strength values.

Key findings include:

- Age-dependent Model Performance:
 - ✓ At 28 days: The models show excellent predictive capability with R² values ranging from 0.75 to 0.98, indicating strong correlations between predicted and observed strength values across all SCM types.
 - ✓ At 60 days: The models demonstrate superior performance with R² values between 0.95-0.97, showing improved predictive accuracy for long-term strength development.
- Heat Treatment Effects: The 3D response surfaces clearly demonstrate that heat treatment significantly influences compressive strength development. The color gradients in the response surfaces show distinct strength variations between heat-treated and non-heat-treated specimens across all age periods.
- SCM Dosage Optimization: SCM dosage exhibited a quadratic relationship with strength, where replacement levels of 10% to 20% provided optimal performance, while 30% replacement tended to reduce compressive strength. This non-linear behavior is clearly visible in the 3D response surfaces across all mineral additions.
- Multi-factor Interactions: The 3D surfaces demonstrate significant interactions between heat treatment, SCM dosage, and age period, indicating that the combined effects of these factors are non-additive and require careful optimization for maximum strength development.

The close alignment of data points with regression lines confirms the statistical robustness of the predictive models for both 28-day and 60-day compressive strength estimation.

4.2.5.1.4 Validation of the Statistical Model

The alignment between predicted and observed values is presented in Figure 4.18, demonstrating the model's accuracy in predicting CS28. Similarly, Figure 4.19 confirms the model's predictive capability at 60 days. The high R² values further validate the robustness of the model, confirming its suitability for optimizing HPC mix design.

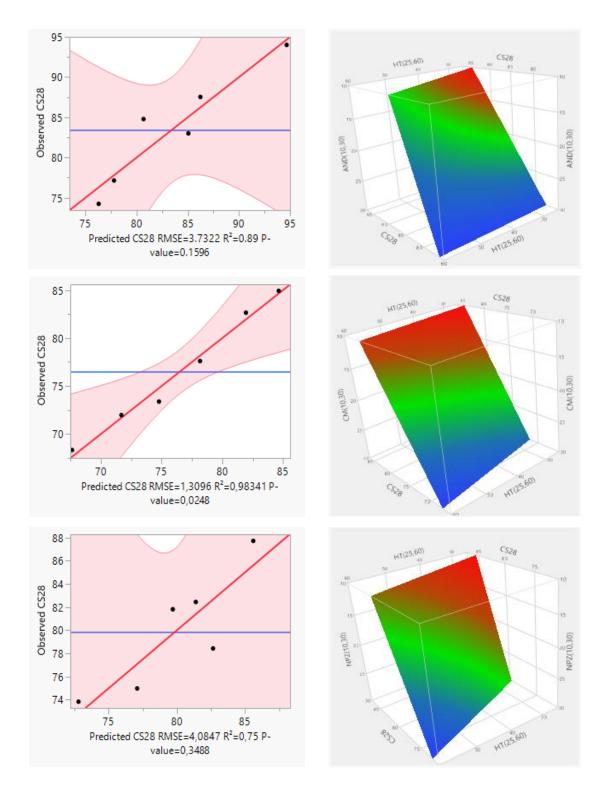


Figure 4.18: Relationship between 28-day compressive strength (CS28), heat treatment, and SCM dosage, presenting a comparison of predicted and experimental values alongside a response surface plot

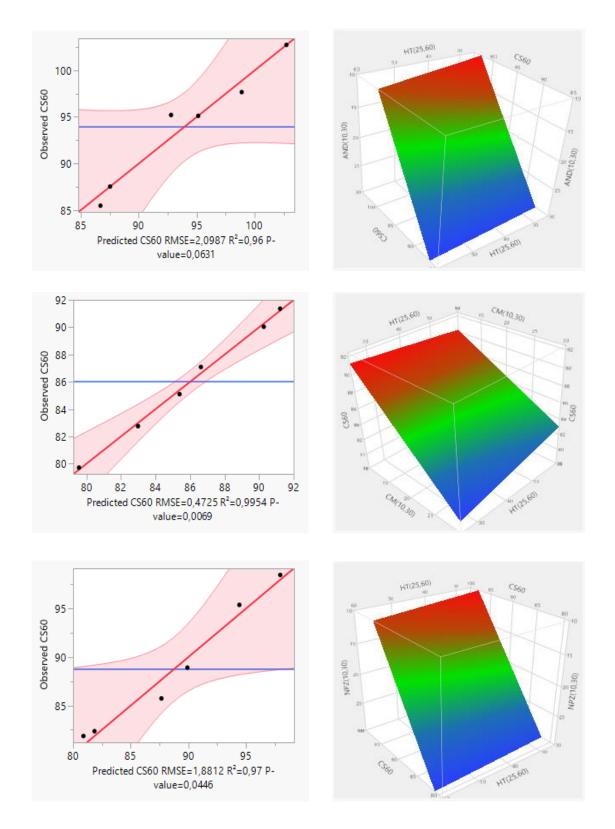


Figure 4.19: 60-day compressive strength (CS60), highlighting model validation and strength progression over time.

4.2.5.2 Optimization of HPC Mix Design Through Predictive Modeling

4.2.5.2.1 Effect of Heat Curing on SCM Optimization

The influence of heat curing on strength development is evident from the predictive equations, where:

- Elevated temperatures accelerate early hydration, particularly in mixtures containing calcined marl (CM) and natural pozzolan (NPZ), resulting in significant strength gains at 1 and 7 days.
- Beyond 28 days, long-term performance is predominantly influenced by pozzolanic reactivity, with non-heat-treated (NT) samples exhibiting sustained strength development due to continued secondary hydration.
- An optimal SCM dosage of 10%–20% is identified as the most effective for maintaining high compressive strength at later curing ages, whereas excessive replacement levels (≥30%) may lead to higher porosity and reduced mechanical performance.

4.2.5.2.2 Predictive Modeling for Compressive Strength Optimization

By applying regression analysis, optimal mix proportions can be identified based on specific performance requirements:

- For precast applications → Heat-treated HPC with 10% SCM ensures rapid strength gain, allowing for early formwork removal and accelerated construction schedules.
- For structural applications demanding long-term strength and durability → Non-heattreated HPC with 20% SCM achieves greater ultimate strength, making it ideal for infrastructure projects.
- For cost-efficient cement reduction \rightarrow 30% SCM substitution is feasible, but adjustments in water-to-binder ratio (W/B) and admixture dosage are necessary to counteract potential strength losses.

By leveraging this statistical approach, engineers can achieve precise control over HPC properties, ensuring optimal performance for specific applications while promoting sustainable construction practices.

GENERAL CONCLUSION

C H A P Ţ B R



CHAPTER -5:

General Conclusion: "Key Findings and Future Perspectives in Sustainable High-Performance Concrete Development"

5 General Conclusion

The pursuit of sustainable and high-performance concrete (HPC) has gained significant traction in contemporary civil engineering research. As the construction industry faces increasing demands for environmentally friendly materials, the integration of locally sourced mineral additions has emerged as a promising solution. This study explored the potential of andesite and calcined marl—two abundant mineral resources in Algeria—as supplementary cementitious materials (SCMs) for enhancing HPC. By systematically evaluating their impact on rheological behavior, mechanical properties, and durability under both normal and heat-treated conditions, this research provides a scientifically grounded approach to optimizing sustainable concrete formulations. The findings contribute to a growing body of knowledge that seeks to align advanced concrete technology with sustainable development goals, particularly by reducing reliance on conventional cementitious materials and minimizing environmental impact.

5.1 Synthesis of Major Findings

This research has comprehensively examined the influence of three locally sourced mineral additions—andesite (AND), calcined marl (CM), and natural pozzolan (NPZ)—on the curing behavior, rheological performance, and durability of heat-treated high-performance concrete (HPC). While andesite and calcined marl were the focus of the study, natural pozzolan was incorporated as a reference SCM, enabling comparative evaluation of performance across all mixtures. The experimental investigation provided significant insights into both the fresh and hardened state properties of HPC, highlighting the potential of these mineral additions in advancing sustainable and durable concrete technologies.

5.1.1 Influence on Fresh State Properties

The workability of HPC varied significantly depending on the type and dosage of the supplementary cementitious materials (SCMs). The following key observations were noted:

- ♣ Slump flow and workability: Andesite-based HPC exhibited a gradual reduction in slump flow with increasing replacement levels due to its angular particle morphology and reduced water retention capacity. Calcined marl, due to its fine nature and high reactivity, led to early water absorption, significantly reducing workability.
- ♣ Superplasticizer efficiency: Higher SCM dosages required increased superplasticizer content to maintain workability. CM-based HPC exhibited the highest water demand, whereas NPZ-based HPC maintained stable fluidity due to its rounded morphology.
- ♣ Absolute Density and air content: The absolute density of HPC mixtures remained relatively stable for SCM replacement levels up to 20%, but at higher dosages (≥30%), an increase in air entrapment led to a slight decrease in density and homogeneity.

5.1.2 Impact on Mechanical Performance

The incorporation of andesite and calcined marl significantly influenced the compressive strength development of HPC across different curing ages and heat treatment conditions:

- ♣ Early-age strength: Heat-treated (HT) specimens demonstrated accelerated strength gain, reaching up to 52.44 MPa at 1 day, attributed to enhanced hydration kinetics under elevated temperatures. The thermal curing effect was particularly beneficial for SCM contents of 10% to 20%.
- Long-term strength development: Non-heat-treated (NT) samples exhibited superior strength retention at 60 days due to sustained pozzolanic activity. NT samples incorporating 20% andesite or calcined marl surpassed their HT counterparts, indicating that prolonged hydration enhances long-term mechanical performance.
- ♣ Optimal replacement levels: A 10% to 20% replacement level of SCMs provided the best balance between early and long-term strength. At 30% replacement, excessive water demand and incomplete pozzolanic reactions contributed to slight reductions in compressive strength.

5.1.3 Durability and Transport Properties

- ♣ Porosity and water absorption: The addition of SCMs improved matrix densification, with 10%-20% SCM replacements leading to reduced porosity. However, at 30% replacement, increased void content was observed, which could potentially affect long-term durability.
- ♣ Ultrasonic pulse velocity (UPV): All mixtures exhibited high UPV values (≥4500 m/s), confirming their dense microstructure. HT samples initially demonstrated slightly lower UPV due to internal microcracking but retained acceptable values over time.

♣ Acid resistance: HPC mixtures incorporating calcined marl exhibited the highest resistance to sulfuric acid exposure, retaining over 80% of their 60-day compressive strength, reinforcing its suitability for aggressive environments.

5.1.4 Statistical Modeling and Optimization

- ♣ Design of Experiments (DOE) methodology: This study employed DOE techniques to systematically analyze the influence of SCM content and curing conditions on HPC performance. Statistical modeling helped identify optimal mix compositions for maximizing compressive strength and durability.
- Regression models and ANOVA analysis: Predictive models were developed to quantify the impact of SCM dosage and thermal curing on strength evolution, with high R² values close to 1 indicating strong model reliability.
- ♣ Optimization of mix proportions: The DOE analysis confirmed that 10%-20% SCM replacement provides the best balance between early-age strength (for precast applications) and long-term durability (for structural elements). Higher SCM dosages (≥30%) necessitate adjustments in mix design to mitigate strength variability and porosity increases.

5.2 Practical Implications for the Construction Industry

The findings of this study underscore the potential of using local Algerian minerals—andesite and calcined marl—as sustainable alternatives to traditional SCMs in HPC applications. The practical benefits include:

- ♣ Cost reduction and resource efficiency: Utilizing local mineral resources reduces reliance on imported SCMs, promoting economic sustainability in Algeria.
- ◆ Optimized mix design for durability: The results suggest that optimal replacement levels (10%-20%) can enhance mechanical performance and durability, making HPC more suitable for precast elements, high-rise structures, and infrastructure projects.
- ♣ Heat treatment in precast applications: Thermal curing is effective for early-age strength development in precast concrete production, where rapid strength gain is essential for demolding and accelerating construction schedules.
- ♣ Data-driven decision making: The integration of DOE methodologies allows for precise optimization of mix compositions, reducing trial-and-error approaches in industrial applications.

5.3 Limitations and Future Research Directions

Despite the contributions of this study, certain limitations should be acknowledged:

- ♣ Durability assessment scope: Future research should include evaluations of resistance to freeze-thaw cycles, chloride ingress, and alkali-silica reaction to provide a comprehensive understanding of long-term performance.
- ♣ Microstructural evolution analysis: Advanced microscopy techniques such as nanoindentation and X-ray microtomography could further elucidate the effects of SCMs on interfacial transition zones and cementitious gel development.
- ♣ Field-scale validation: Implementing large-scale structural testing will be essential to bridge the gap between laboratory findings and real-world performance of these HPC formulations.
- ♣ Expanded statistical modeling: Future studies should refine predictive models by incorporating additional variables such as temperature variations, alternative curing methods, and real-time performance monitoring in construction sites.

5.4 Final Conclusion

This research has demonstrated that local andesite and calcined marl possess significant potential as supplementary cementitious materials in high-performance concrete. By enhancing mechanical properties, reducing porosity, and improving durability, these mineral additions align with global sustainability objectives, offering a viable pathway to reducing cement consumption and associated CO₂ emissions. The dual approach of utilizing thermal curing for early strength development while capitalizing on prolonged pozzolanic activity in normal curing regimes presents a strategic advantage for optimizing HPC formulations.

Moving forward, the findings of this study lay a foundation for further exploration into the broader application of local mineral additions in sustainable construction. By integrating advanced characterization techniques, expanding field-scale research, and refining mix design methodologies through statistical optimization, the potential of indigenous materials can be fully harnessed to develop next-generation, environmentally responsible high-performance concrete. The commitment to leveraging local resources for innovative construction solutions underscores a fundamental shift towards more sustainable, resilient, and economically viable building practices worldwide.

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ANNEXE

Annexe 1: Mechanical and durability properties of hardened HPC

			EW	CS-1	CS-7	P	WAC	UPV	CS-28	CS-60	CS-60	CS-60
											Acid	Red.
			(%)	(MPa)	(MPa)	(%)	(%)	(m/s)	(MPa)	(MPa)	(MPa)	(%)
HPC-10 AND	NT	Mean	/	28.62	74.95	2.17	0.91	4677.43	94.01	102.74	62.65	39
		SD	/	1.53	4.59	0.15	0.10	68.86	1.73	2.63	2.80	1.16
		CoV	/	5.34	6.12	7.04	10.60	1.47	1.84	2.56	4.46	2.98
	НТ	Mean	0.77	48.38	77.64	2.03	0.94	4486.41	83.01	97.67	60.50	38
		SD	0.04	2.42	2.32	0.12	0.05	82.11	2.48	3.56	0.27	2.00
		CoV	5.33	5.00	2.99	5.69	5.06	1.83	2.98	3.65	0.45	5.25
HPC-20 AND	NT	Mean	/	29.89	70.53	2.1	0.88	4801.99	87.54	95.12	57.25	40
		SD	/	2.35	3.74	0.10	0.08	109.00	1.05	2.57	8.56	7.82
		CoV	/	7.86	5.31	4.76	8.55	2.27	1.20	2.71	14.96	19.58
	нт	Mean	0.76	52.44	79.08	1.93	0.91	4512.91	84.79	95.21	49.66	48
		SD	0.06	3.02	0.43	0.06	0.06	95.25	3.59	5.43	0.49	2.76
		CoV	8.12	5.75	0.55	2.99	6.59	2.11	4.23	5.70	1.00	5.78
HPC-30 AND	NT	Mean	/	25.84	68.31	2.57	1.05	4765.77	77.15	87.53	47.47	46
		SD	/	1.02	1.39	0.06	0.09	6.51	2.92	4.31	6.36	4.57
		CoV	/	3.94	2.04	2.25	8.41	0.14	3.79	4.93	13.40	9.96
	нт	Mean	0.88	40.30	71.76	2.20	0.92	4665.82	74.25	85.48	44.72	48
		SD	0.04	1.73	5.42	0.20	0.07	22.51	1.19	4.11	3.83	2.02
		CoV	4.94	4.28	7.55	9.09	7.57	0.48	1.61	4.81	8.56	4.23
HPC-10 CM	NT	Mean	/	23.82	74.49	2.40	0.99	4746.89	84.93	91.36	43.68	52
		SD	/	2.06	0.62	0.26	0.11	6.45	2.56	1.74	2.94	2.40
		CoV	/	8.65	0.83	11.02	11.28	0.14	3.02	1.90	6.74	4.60

	нт	Mean	0.62	40.85	74.51	2.40	0.96	4725	82.65	90.04	48.22	46
		SD	0.07	2.01	2.13	0.20	0.06	61.45	2.25	1.52	3.68	3.21
		CoV	10.77	4.93	2.86	8.33	6.28	1.30	2.73	1.69	7.63	6.90
HPC-20 CM	NT	Mean	/	23.74	66.14	2.27	0.94	4796.26	77.61	85.1	45.73	46
		SD	/	3.49	2.03	0.25	0.10	23.00	3.88	2.61	7.31	7.15
		CoV	/	14.70	3.08	11.09	10.43	0.48	5.01	3.06	15.98	15.41
	HT	Mean	0.76	37.41	71.81	2.40	0.97	4669.38	73.39	87.09	45.83	47
		SD	0.05	2.38	6.57	0.17	0.06	12.73	4.24	4.46	1.02	2.04
		CoV	7.03	6.35	9.15	7.22	6.44	0.27	5.78	5.13	2.23	4.32
HPC-30 CM	NT	Mean	/	25.64	63.62	2.17	0.90	4754.38	71.98	79.72	40.71	49
		SD	/	3.12	3.22	0.12	0.06	6.51	3.66	5.59	5.95	3.93
		CoV	/	12.16	5.07	5.32	6.36	0.14	5.08	7.01	14.60	8.01
	нт	Mean	0.89	35.69	65.76	2.30	0.98	4680.45	68.34	82.76	44.26	47
		SD	0.06	2.72	4.54	0.10	0.09	33.54	2.49	3.49	4.36	3.08
		CoV	6.42	7.62	6.91	4.35	9.28	0.72	3.64	4.22	9.84	6.61
HPC-10 NPZ	NT	Mean	/	28.65	71.65	2.20	0.86	4587.88	87.71	98.49	57.61	42
		SD	/	2.58	5.45	0.10	0.07	42.65	8.28	1.65	6.20	5.40
		CoV	/	8.99	7.61	4.55	7.58	0.93	9.44	1.67	10.76	12.99
	нт	Mean	0.68	49.27	76.66	2.27	0.92	4459.55	82.44	95.4	51.99	46
		SD	0.04	1.92	3.87	0.21	0.07	30.14	7.67	1.27	5.23	4.94
		CoV	6.07	3.90	5.05	9.17	8.13	0.68	9.31	1.33	10.05	10.84
HPC-20 NPZ	NT	Mean	/	32.40	70.09	2.17	0.90	4606.74	78.43	88.92	49.73	44
		SD	/	2.64	3.39	0.15	0.01	26.11	5.51	2.47	4.03	3.03
		CoV	/	8.16	4.83	7.04	1.40	0.57	7.03	2.78	8.10	6.86
	HT	Mean	0.98	51.66	73.47	2.13	0.90	4525.03	74.98	85.74	47.25	45
		SD	0.04	2.70	3.98	0.21	0.13	17.69	3.95	1.75	5.06	4.77
		CoV	4.21	5.24	5.42	9.77	14.10	0.39	5.27	2.05	10.71	10.61

HPC-30 NPZ	NT	Mean	/	26.86	68.1	2.53	1.06	4715.38	81.81	82.36	45.78	44
		SD	/	5.71	2.25	0.23	0.09	163.77	0.83	7.06	4.63	1.54
		CoV	/	21.25	3.30	9.13	8.56	3.47	1.01	8.57	10.12	3.46
	нт	Mean	1.05	45.51	73.87	2.47	1.02	4555.95	73.84	81.86	45.81	44
		SD	0.04	4.58	1.26	0.21	0.08	17.94	4.96	1.81	5.02	5.21
		CoV	4.17	10.06	1.70	8.43	7.46	0.39	6.71	2.21	10.97	11.82

Note: **HPC**: High-Performance Concrete, **AND**: Andesite, **CM**: Calcined Marl, **NPZ**: Natural Pozzolan, **NT**: Non-Heat-Treated, **HT**: Heat-Treated, **SD**: Standard Deviation, **CoV**: Coefficient of Variation (%), **EW**: Evaporated Water, **CS-D**: Compressive Strength at D days, where D = 1, 7, 28, and 60 days, **P**: Porosity, **WAC**: Water Absorption Capacity, **UPV**: Ultrasonic Pulse Velocity, **CS-60 Acid**: Compressive Strength of HPC Mixtures at 60 Days Post Sulfuric Acid Immersion, **CS-60 Red.**: Percentage Strength Loss of Samples Exposed to Sulfuric Acid.



SPA BISKRIA CIMENT



FICHE TECHNIQUE CEM I 42.5R CIMENT PORTLAND

CEM I 42.5R Ciment portland, pour les bétons hautes performances et a une résistance rapide à court terme, destiné aux domaines où les délais de décoffrage sont courts, il est recommandé particulièrement pour le bétonnage par temps froid

CEM | 42.5R :

Conforme à la norme Algérienne (NA442-2013)

★ DOMAINES D'APPLICATION

Un ciment pour tous vos travaux de constructions de haute résistance a jeune âge, il est aussi recommandé pour les utilisations suivantes :

- Produits en bétons qui demandent un durcissement rapide.
- Le bétonnage dans des coffrages coulissant, surtout en période hivernale.
- Béton résistant au gel en présence de sels de déverglacâge.
- Tabliers de ponts.
- Béton pompé.
- Béton projeté



✓ APPLICATIONS RECOMMANDÉES

- Béton armé à haute résistance.
- Béton autoplaçant.

FORMULATION CONSEILLÉE

	ciment	Sable (sec) 0/5	Gravillons(sec)	Eau (litres)
Dosage pour béton	50k X1	+ X7 😭	+ X5 + X4	+ 25 L
	ciment	Sable Correcteur 0/1mm	Sable (sec)	Eau (litres)
Mortier de briquetage	50k X1	+ X6 😭	+ X9 😭	+ 35 L
Mortier de finitions	50k X1	+ X9 😭	+ X6 😭	+ 35 L

Q CARACTÉRISTIQUES TÉCHNIQUES

Remarque: un bidon =10 litres

Analyses chimiques (%)	valeur
Perte au feu	2.6 – 3.7
Teneur en sulfates (SO3)	2.2 – 2.8
Teneur en Oxyde de Magnésium (MgO)	1.7 – 2.8
Teneur en Chlorures (Cl ⁻)	0.03 - 0.07
Composition Potentielle du Clinker (Selon Bogue) (%)	valeur
C ₃ S	56 – 66
C3A	5.1 – 7.2
Propriétés physiques	valeur
Consistance normale (%)	25.8 – 26.4
Expansion à chaud (mm)	0.25 - 1.0
Temps de prise (min)	valeur
Début de prise	150 – 190
Fin de prise	220 – 250
Résistance à la compréssion	valeur
2 jours (MPa)	20 – 29
28 jours (MPa)	42.5 – 52.5





SPA BISKRIA CIMENT Adresse : Djar Belahrache Branis , Biskra Algerie Tel:+213 (0) 560 753 424 Fax:+213 (0) 33 558 108 contact@biskriaciment-dz.com www.biskriaciment-dz.com

Annexe 3: Technical Data Sheet- Superplasticizer.

annexe 5

NOTICE TECHNIQUE

2 1 1

MEDAFLOW 30

Conforme à la norme EN 934-2:TAB 1, TAB 3.1

Super plastifiant Haut réducteur d'eau

DESCRIPTION

Le **MEDAFLOW 30** est un super plastifiant haut réducteur d'eau de la troisième génération. Il est conçu à base de polycarboxylates d'Ether qui améliorent considérablement les propriétés des bétons.

Le **MEDAFLOW 30** permet d'obtenir des bétons et mortiers de très haute qualité.

En plus de sa fonction principale de superplastifiant, il permet de diminuer la teneur en eau du béton d'une façon remarquable.

Le MEDAFLOW 30 ne présente pas d'effet retardateur.

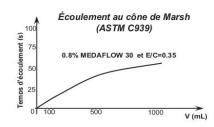
DOMAINES D'APPLICATION

- · Bétons à hautes performances
- · Bétons auto plaçant
- · Bétons pompés
- Bétons précontraints
- Bétons architecturaux.

PROPRIÉTÉS

Grâce à ses propriétés le **MEDAFLOW 30** permet : Sur béton frais :

- Obtention d'un rapport E/C très faible
- Amélioration considérable de la fluidité
- Une très bonne maniabilité
- Éviter la ségrégation
- Faciliter la mise en œuvre du béton



Sur béton durci :

- Augmenter les résistances mécaniques à jeune âge et à long terme (voir tableau).
- Diminuer la porosité
- Augmenter la durabilité
- Diminuer le retrait et le risque de fissuration

Désignation		Rc (MPa)	
	3J	7J	28J
MEDAFLOW 30 (1.4%)	39.2	54.7	62.2

CARACTÉRISTIQUES

• Aspect	Liquide
Couleur	
• pH	6 – 6,5
Densité	1,07 ± 0,01
• Teneur en chlore	< 0,1 g/l
Extrait sec	30%

MODE D'EMPLOI

Le **MEDAFLOW 30** est introduit dans l'eau de gâchage.

Il est recommandé d'ajouter l'adjuvant dans le béton après que 50 à 70% de l'eau de gâchage ait déjà été introduite.

DOSAGE

Plage de dosage recommandée :

0,5 à 2,0 % du poids de ciment soit 0.46 à 1.85 litre pour 100 Kg de ciment.

Le dosage optimal doit être déterminé sur chantier en fonction du type de béton et des effets recherchés.

CONDITIONNEMENT ET STOCKAGE

Les renseignements donnés dans cette notice sont basés sur notre connaissance et notre expérience à ce jour. Il est recommandé de procéder à des essais de convenance pour déterminer la fourchette d'utilisation tenant compte des conditions réelles de chantier.



Zone industrielle Oued Smar – BP85 Oued Smar – 16270 Alger Tél : (213) 021 51 66 81 & 82 Fax : (213) 021 51 64 22 & 021 51 65 23 www.granitex-dz.com - E-mail: granitex@granitex-dz.com





MEDAFLOW 30

Le **MEDAFLOW 30** est conditionné en bidons de 10Kg, fûts de 210 Kg et 240 Kg, cubiténaire 1100kg.

Délai de conservation :

Une année dans son emballage d'origine, à l'abri du gel et de la chaleur (5° C < t < 35° C). Lors d'une exposition du produit au soleil, sa couleur est sujette à changer de ton.

PRÉCAUTIONS D'EMPLOI

Manipulation non dangereuse. Se référer à la Fiche de Données de Sécurité disponible sur : www.granitex-dz.com

PV d'essais conforme aux normes, établi par le **CNERIB** en Avril 2005.

NB: Les produits à base de polycarboxylates d'Ether (PCE), exposé aux UV, changent dans la couleur mais sans aucun incident sur les propriétés et les effets de l'adjuvant.

Les renseignements donnés dans cette notice sont basés sur notre connaissance et notre expérience à ce jour. Il est recommandé de procéder à des essais de convenance pour déterminer la fourchette d'utilisation tenant compte des conditions réelles de chantier.

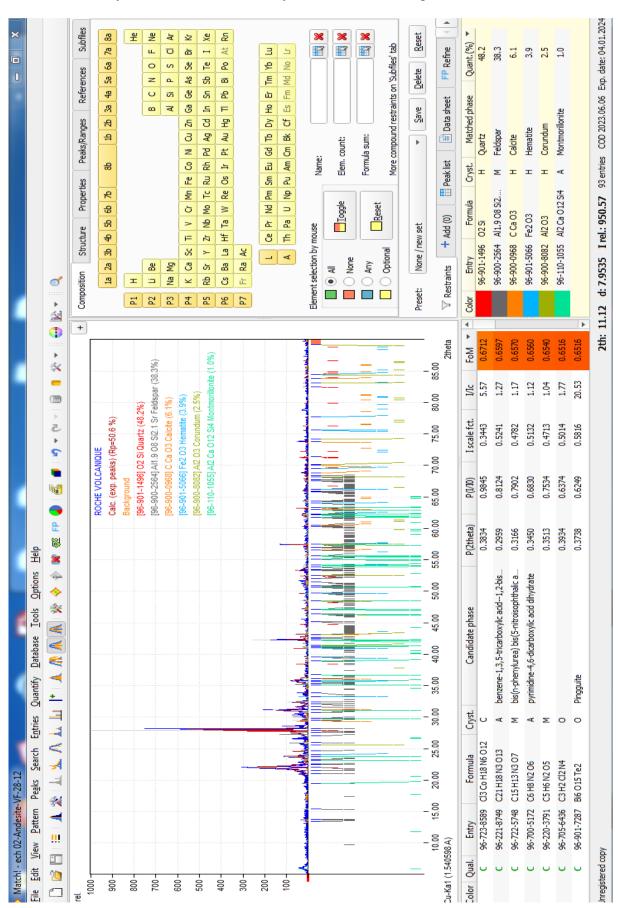


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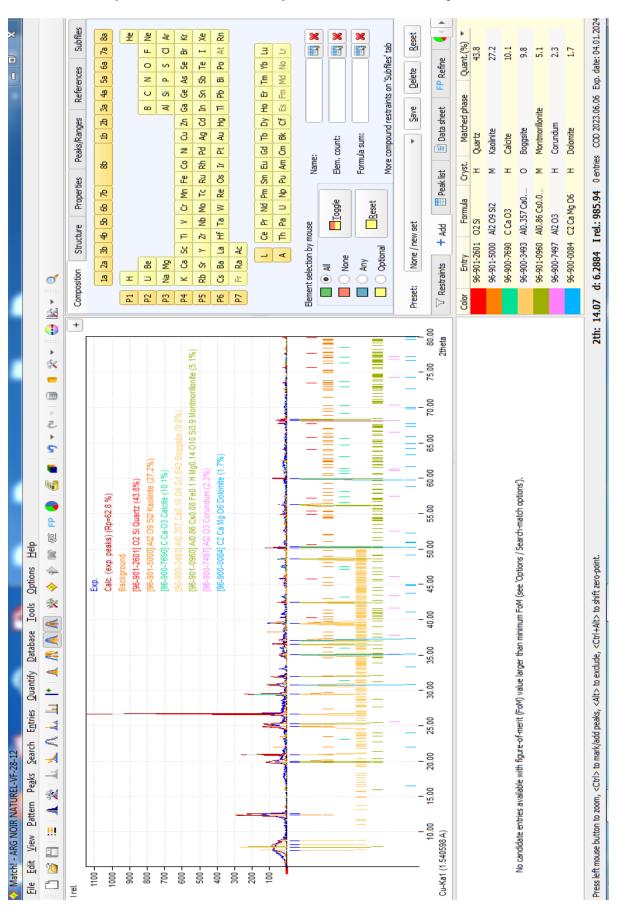
Fax: (213) 021 51 64 22 & 021 51 65 23 www.granitex-dz.com - E-mail: granitex@granitex-dz.com Cofr Cofr Connect Conn

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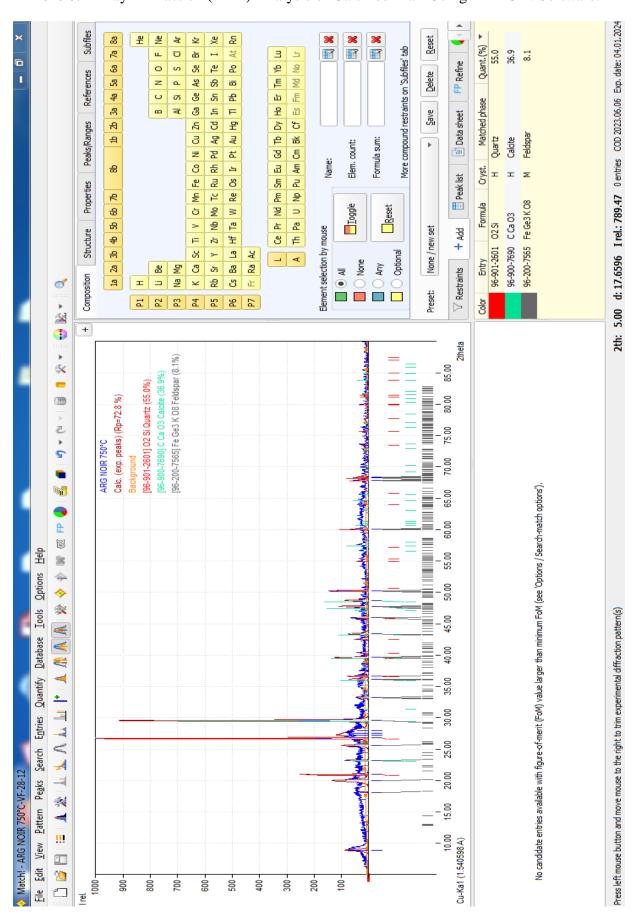
Annexe 4: X-Ray Diffraction (XRD) Analysis of Andesite Using MATCH! Software.



Annexe 5: X-Ray Diffraction (XRD) Analysis of Naturel Marl Using MATCH! Software.



Annexe 6: X-Ray Diffraction (XRD) Analysis of Calcined Marl Using MATCH! Software.



Annexe 7: X-Ray Diffraction (XRD) Analysis of Natural Pozzolan Using MATCH! Software.

