



الجمهورية الجزائرية الديمقراطية الشعبية
People's Democratic Republic of Algeria
وزارة التعليم العالي والبحث العلمي
Ministry of Higher Education and Scientific Research
– جامعة الشهيد شيخ العربي التبسي تبسة
Echahid Cheikh Larbi Tebessi University – Tebessa
معهد المناجم
Mining Institute
قسم المناجم والجيوتكنولوجيا



Option: Geotechnic

Improving expansive soils using geopolymer.

Presented by: BELAHCENE Cheyma.

Board of Examiners

AMRANI Dounia	Examiner	MAA	Echahid Cheikh Larbi Tebessi University – Tebessa
HAMDANE Ali	Supervisor	MAA	Echahid Cheikh Larbi Tebessi University – Tebessa
BENGHAZI Ziyed	Co-supervisor	MCA	Echahid Cheikh Larbi Tebessi University – Tebessa

2024/2025

الإهداء

بسم الله الرحمن الرحيم،

الحمد لله الذي بنعمته تتمّ الصالحات،

وما كان لهذا العمل أن يرى النور لولا توفيق الله عزّ وجل

إلى من كانا سببًا بعد الله في دعمي وصبري،

إلى والديّ العزيزين، حفظهما الله وأطال في عمرهما

وإلى عائلتي الكريمة وكل من وقف إلى جانبي،

أهدي هذا الجهد المتواضع،

سائلًا الله أن يجعله خالصًا لوجهه الكريم،

وأن ينفع به ويبارك فيه.



Acknowledgement

I would never have done this work without my guidance
The supervisor, Mr HAMDANE Ali , who was the source
Knowledge, wisdom and patience through this research

I also deeply thank

And Great respect

For Mr. Ben Ghazi Ziyad Co-supervisor, and all

Geotechnical teachers.

I thank the workers of the university laboratory and the workers of the public works
laboratory of the wilaya of Annaba and Tebessa

And to everyone who helped me in conducting this research, even with a kind word and a
beautiful smile



Abstract

Expansive soils pose significant challenges in geotechnical engineering due to their pronounced volume change behavior in response to moisture variations. These soils, which are typically rich in active clay minerals, can induce severe structural damage through swelling and shrinkage, particularly in semi-arid regions such as northeastern Algeria. Conventional stabilization methods, including lime and ordinary Portland cement, have been widely used to mitigate these problems; however, their high environmental impact and durability limitations have motivated the search for more sustainable alternatives.

This thesis investigates the effectiveness of geopolymer binders derived from industrial by-products as a sustainable solution for the stabilization of expansive soils. The studied soil was collected from Jbel Dukkan in the Tebessa region and was first subjected to a comprehensive geotechnical characterization, including physical, chemical, and mechanical tests, to confirm its expansive nature. Geopolymer stabilization was then carried out using Ground Granulated Blast Furnace Slag (GGBFS) and iron mine waste at different binder contents. The treated soils were evaluated through compaction, plasticity, and swelling-related tests to assess the impact of geopolymer treatment.

The results demonstrate that geopolymer stabilization significantly reduces soil plasticity and swelling potential while improving compaction characteristics and mechanical performance. The formation of aluminosilicate geopolymer gels led to enhanced soil structure, reduced moisture sensitivity, and increased stability. These findings confirm that geopolymer binders represent an effective and environmentally sustainable alternative to conventional stabilizers for expansive soil improvement.

Résumé

Les sols gonflants constituent un problème majeur en géotechnique en raison de leur forte sensibilité aux variations de teneur en eau, qui se traduit par des phénomènes de gonflement et de retrait. Riches en minéraux argileux actifs, ces sols peuvent provoquer des désordres importants dans les ouvrages de génie civil, notamment dans les régions semi-arides telles que le nord-est de l'Algérie. Les méthodes traditionnelles de stabilisation, comme la chaux et le ciment Portland, sont couramment utilisées, mais elles présentent des inconvénients liés à leur impact environnemental et à leur durabilité.

Ce mémoire vise à étudier l'efficacité des liants géopolymères issus de sous-produits industriels pour la stabilisation des sols gonflants. Le sol étudié a été prélevé à Djebel Dukkan, dans la région de Tébessa, et a fait l'objet d'une caractérisation géotechnique complète afin de confirmer son caractère gonflant. La stabilisation a ensuite été réalisée à l'aide de géopolymères à base de laitier de haut fourneau moulu (GGBFS) et de déchets miniers de fer, introduits à différents pourcentages. Les sols traités ont été évalués à travers des essais de plasticité, de gonflement et de compactage. Les résultats obtenus montrent une réduction significative de la plasticité et du potentiel de gonflement du sol, accompagnée d'une amélioration des caractéristiques mécaniques et de compactage. La formation de gels aluminosilicatés géopolymères a permis de renforcer la structure du sol et de limiter sa sensibilité à l'eau. Cette étude démontre que les géopolymères constituent une alternative efficace et durable aux méthodes traditionnelles de stabilisation des sols gonflants.

ملخص

تُعدّ الترب الانتفاخية من أكثر أنواع الترب إشكالية في الهندسة الجيوتقنية، وذلك بسبب حساسيتها العالية لتغيرات المحتوى المائي وما ينتج عنها من ظواهر الانتفاخ والانكماش. وتحتوي هذه الترب عادةً على معادن طينية نشطة، مما يؤدي إلى أضرار جسيمة في المنشآت الهندسية، خاصة في المناطق شبه الجافة مثل شمال شرق الجزائر. وعلى الرغم من استعمال الطرق التقليدية لتثبيت الترب، مثل الجير والإسمنت البورتلاندي، إلا أن تأثيرها البيئي المرتفع ومحدودية متانتها على المدى الطويل دفعت إلى البحث عن بدائل أكثر استدامة. يهدف هذا العمل إلى دراسة فعالية الروابط الجيوبوليميرية المشتقة من المخلفات الصناعية في تثبيت الترب الانتفاخية. تم أخذ عينة التربة من منطقة جبل الدكان بولاية تبسة، وأجريت عليها مجموعة من الاختبارات الجيوتقنية الفيزيائية والكيميائية والميكانيكية لتأكيد طبيعتها الانتفاخية. بعد ذلك، تم تثبيت التربة باستخدام جيوبوليميرات قائمة على خبث الأفران العالية المطحون (GGBFS) ومخلفات مناجم الحديد بنسب مختلفة. وقد تم تقييم خصائص التربة المعالجة من خلال اختبارات اللدونة والانتفاخ والدمك. أظهرت النتائج انخفاضًا ملحوظًا في مؤشر اللدونة ونسبة الانتفاخ، إلى جانب تحسن واضح في الخصائص الميكانيكية وقابلية الدمك. ويُعزى ذلك إلى تشكل شبكة جيوبوليميرية ألومينوسيليكاتية حسّنت من بنية التربة وقلّلت من حساسيتها للماء. وتؤكد هذه النتائج أن التثبيت بالجيوبوليميرات يُعدّ حلاً فعالاً ومستدامًا لتثبيت الترب الانتفاخية، وبدلياً واعدًا للطرق التقليدية في الهندسة الجيوتقنية.

Table of Content

Table des matières

Thanks	Erreur ! Signet non défini.
Abstract	4
Résumé	5
Notation	11
General Introduction	1
Chapter 1: Fundamentals of Expansive Soils: Properties, Mechanisms, and Engineering Implications	
1.1 Introduction	3
1.2 Definition of Swelling Soils	3
1.3 Mineral Composition of Swelling Soils	4
1.4 Physical and Mechanical Properties of Expansive Soils	6
1.5 Swelling Mechanism	7
1.6 Problems in Geotechnical Engineering	8
➤ Differential Movement and Structural Damage	8
➤ Uplift and Settlement of Foundations	8
➤ Damage to Pavements and Roads	9
➤ Lateral Thrust on Walls and Structures	9
➤ Slope Instability and Soil Movement	9
1.7 Traditional Treatment Methods	10
1.7.1 Mechanisms of Traditional Chemical Stabilization	10
1.7.2 Lime Stabilization	11
1.7.3 Cement Stabilization	12
1.7.4 Fly Ash and Supplementary Additives	12
1.8 Global Distribution of Expansive Soils	14
1.8.1 Worldwide Occurrence	14
1.8.2 Regional Examples	15
1.8.3 Climatic Influence on Distribution	15
1.8.4 Engineering and Socioeconomic Impacts	15
1.9 Conclusion	16

Chapter 2: Geopolymer Binders for Soil Stabilization: Materials, Mechanisms, and Engineering Performance

2.1 Introduction	18
2.2 Definition and background	18
2.3 Raw Materials and Alkaline Activators	20
2.3.1 Aluminosilicate Raw Materials	20
2.3.2 Chemical Composition and Reactivity of Raw Materials	20
2.3.3 Physical Characteristics of Raw Materials	21
2.3.4 Role of Raw Materials in Soil Stabilization	21
2.3.5 Alkaline Activators in Geopolymer Synthesis	22
2.3.6 Influence of Activator Concentration and Ratios	22
2.4 Geopolymerization Mechanism.....	23
2.4.1 Alkaline Activation: Creating a Reactive Environment.....	23
2.4.2 Dissolution of Aluminosilicate Precursors.....	24
2.4.3 Hydrolysis and Formation of Reactive Species.....	24
2.4.4 Polycondensation and Network Development	25
2.4.5 Gelation and Hardening.....	25
2.4.6 Role of Alkali Ions and Water in Microstructure Development.....	25
2.4.7 Microstructural Evolution and Defect Development.....	26
2.4.8 Influence of Curing Conditions	26
2.5 Properties of Geopolymers	27
2.5.1 Introduction	27
2.5.2 Physical Properties	28
2.5.3 Mechanical Properties	29
2.5.4 Microstructure and Mechanical Performance.....	29
2.5.5 Durability and Long-Term Performance	30
2.6 Interaction with Swelling Soils	30
2.6.1 Reduction of Swelling Through Chemical and Physical Mechanisms.....	31
2.6.2 Microstructural Improvements and Pore Network Modification	32
2.6.3 Strength and Engineering Performance Enhancements.....	32
2.6.4 Durability and Long-Term Stability.....	33
2.7 Advantages for Soil Improvement.....	33
2.7.1 Superior Engineering Performance	33
2.7.2 Enhanced Durability and Microstructural Stability.....	33
2.7.3 Environmental Sustainability	34

2.7.4 Economic and Resource Efficiency.....	35
2.7.5 Applicability Across Diverse Soil Types	35
2.7.6 Contribution to Circular Economy and Sustainability Goals	35
2.8 Conclusion.....	35

**Chapter 3 :Materials, Experimental Program, and Methodology for Geopolymer
Stabilization of Expansive Soil**

.1 Introduction	38
3.2 Soil Sampling and Site Description.....	38
3.3 Soil Characterization	39
3.3.1 Physical Tests	39
3.3.2 Chemical Tests	41
3.3.3 Mechanical Tests	42
3.4 Results	43
3.5 Discussion	43
3.6 Geopolymer Stabilization Methodology	44
3.6.1 Materials Used.....	44
3.6.2 Preparation of Geopolymer Materials	45
3.6.3 Mixing Proportions.....	45
3.6.4 Mixing and Compaction Procedure.....	46
3.6.5 Curing Conditions After compaction	46
3.6.6 Comparison of Soil Properties Before and After Geopolymer Treatment	47
3.7 Conclusion.....	48
General Conclusion and Prospects	50
References	51

List Figure	N° page
Figure 1.1: Illustration of soil swelling and shrinkage behavior [1]	04
Figure 1.2. Clay mineral structure in expansive soils [4]	05
Figure 1.3. Mechanism on the swelling pressure of expansive soil [6]	08
Figure 1.4: Examples of structural damage caused by swelling soils. [8]	10
Figure 1.5: Mechanical and Chemical Stabilizations methods of expansive soils. [9]	13
Figure 1.6: Global Distribution of Reported Expansive Soil Sites (Nelson et al., 2015). [11]	16
Figure 2.1: Schematic structure of geopolymer network	19
Figure 2.2: Process of Geopolymerization. [17]	27
Fig 3.1: Geographic Location of Djebel Dukkan.	39
Figure 3.2. Particle size analysis test by wet sieving.	40
Figure 3.3. soil's plasticity and swelling test.	40
Figure 3.4. soil's natural moisture test.	41
Figure 3.5 Proctor Compaction Test	41
Figure 3.6 Methylene Blue Test	42
Figure 3.7 Free Swell Test	42
Figure 3.8 Oedometer Test	43
Figure 3.9 Materials Used	45
Figure 3.10 percent of geopolymers materials	46
Figure 3.11 Mixing and Compaction Procedure	46
Figure 3.12 After compaction	47

List Table	N° page
Table 1.1. Mineralogical Composition of Expansive Soils [10]	6
Table 1.2. Physical properties of expansive soils. [3]	7
Table 1.3: Conventional Treatment Methods for Expansive Soils [10]	14
Table 2.1: RAW MATERIALS AND ALKALINE ACTIVATORS USED IN GEOPOLYMERS. [12]	23
Table 2.2: Mechanical and Physical Properties of Geopolymers. [12]	31
Table 2.3: Comparison Between Untreated and Treated Expansive Soils. [9]	34
Table 3.1: tests results	43
Table 3.2: Comparison Between before and after Treating thes Soils	48

Notation

LL	Liquid Limit
PL	Plastic Limit
PI	Plasticity Index
OMC	Optimum Moisture Content
MDD	Maximum Dry Density
P _g	Swelling Pressure
FS	Free Swell
VBS	Valeur au Bleu de Méthylène (Methylene Blue Value)
UCS	Unconfined Compressive Strength
CEC	Cation Exchange Capacity
Si	Silicon
Al	Aluminum
Si/Al	Silicon to Aluminum Ratio
NaOH	Sodium Hydroxide
Na ₂ SiO ₃	Sodium Silicate
GGBFS	Ground Granulated Blast Furnace Slag
Ca ²⁺	Calcium Ion
Na ⁺	Sodium Ion
CSH	Calcium Silicate Hydrate
CAH	Calcium Aluminate Hydrate
N-A-S-H	Sodium Alumino-Silicate Hydrate Gel
C-(N)-A-S-H	Calcium Sodium Alumino-Silicate Hydrate Gel
SEM	Scanning Electron Microscope
OPC	Ordinary Portland Cement
pH	Potential of Hydrogen
wt. %	Weight Percentage
cm ³	Cubic Centimeter
g/cm ³	Gram per Cubic Centimeter

GENERAL INTRODUCTION

General Introduction

Expansive soils represent one of the most problematic ground conditions in geotechnical engineering due to their pronounced sensitivity to moisture variations. These soils, which are typically rich in active clay minerals such as montmorillonite, undergo significant volume changes in response to wetting and drying cycles. Swelling during moisture ingress and shrinkage during drying can induce severe ground movements, leading to differential settlement, heaving of foundations and pavements, cracking of structural elements, and long-term serviceability problems. As a result, expansive soils pose serious challenges to the design, construction, and maintenance of civil engineering infrastructure, particularly in semi-arid and arid regions.

In Algeria, expansive clay formations are widely distributed and have been responsible for numerous cases of structural damage and increased maintenance costs. Traditional soil stabilization methods, such as lime and ordinary Portland cement (OPC), have been extensively employed to mitigate the adverse effects of expansive soils by reducing plasticity and improving strength. However, these conventional techniques are associated with several limitations, including high energy consumption, significant carbon dioxide emissions, durability issues in aggressive environments, and increasing material costs. In the context of global sustainability objectives and the growing demand for environmentally responsible construction practices, there is a pressing need to develop alternative stabilization solutions that are both technically effective and environmentally sustainable.

Geopolymer technology has emerged as a promising alternative to traditional cementitious binders. Geopolymers are inorganic binders produced through the alkaline activation of aluminosilicate-rich materials such as fly ash, ground granulated blast furnace slag, and other industrial by-products. Their formation mechanism, known as geopolymerization, results in a three-dimensional aluminosilicate network characterized by high strength, low permeability, and excellent chemical durability. From a geotechnical perspective, geopolymers offer significant potential for soil stabilization due to their ability to bind soil particles, reduce pore connectivity, limit water ingress, and modify clay mineral activity. In addition, the use of industrial wastes as geopolymer precursors contributes to waste valorization and reduced environmental impact.

The main objective of this thesis is to investigate the effectiveness of geopolymer binders derived from industrial by-products in stabilizing expansive clay soil. The study focuses on evaluating the

influence of geopolymer treatment on the physical, mechanical, and swelling behavior of an expansive soil collected from Jbel Dukkan in the Tebessa region of northeastern Algeria. To achieve this objective, the thesis combines a comprehensive review of expansive soil behavior and geopolymer technology with an experimental investigation involving soil characterization, geopolymer stabilization, and comparative performance analysis.

The structure of the thesis is organized as follows. Chapter 1 presents the fundamental concepts related to expansive soils, including their mineralogical composition, swelling mechanisms, engineering problems, traditional treatment methods, and global distribution. Chapter 2 introduces geopolymer binders, discussing their raw materials, alkaline activators, geopolymerization mechanisms, properties, and interactions with expansive soils, with an emphasis on sustainability and engineering performance. Chapter 3 describes the experimental program, including soil sampling, geotechnical characterization, geopolymer stabilization methodology, and a comparative evaluation of soil behavior before and after treatment. Together, these chapters aim to demonstrate the feasibility and effectiveness of geopolymer stabilization as a sustainable solution for expansive soil improvement.

Chapter 1

Fundamentals of Expansive Soils: Properties, Mechanisms, and Engineering Implications

1.1 Introduction

Expansive soils constitute one of the most challenging ground conditions encountered in geotechnical engineering due to their pronounced volume change behavior in response to moisture variations. These soils, which typically contain high proportions of active clay minerals, undergo swelling upon wetting and shrinkage during drying cycles. Such behavior can induce significant ground movements, leading to structural distress, serviceability problems, and long-term damage to civil engineering infrastructure. As urban development increasingly extends into regions underlain by expansive soils, understanding their behavior has become a critical requirement for safe and sustainable design.

The engineering significance of expansive soils lies not only in their widespread global distribution but also in the complexity of the physicochemical mechanisms governing their response to environmental changes. The presence of smectite-group minerals, particularly montmorillonite, imparts high plasticity, water affinity, and swelling pressure, which directly influence the soil's physical and mechanical properties. In regions characterized by seasonal climatic variations, such as semi-arid and arid zones, these effects are further amplified, making expansive soils a major source of foundation instability, pavement deterioration, and slope failure.

1.2 Definition of Swelling Soils

Swelling soils, also referred to as expansive soils, are a particular category of soils that undergo significant volume changes in response to variations in moisture content. When the water content of these soils increases, they swell or expand, whereas a decrease in moisture content causes them to shrink or contract. This cyclic swelling–shrinkage behavior is mainly attributed to the presence of clay minerals, especially those belonging to the smectite group, such as montmorillonite. These minerals possess a layered crystalline structure capable of absorbing water molecules within their interlayer spaces.

The swelling process occurs when water molecules penetrate the interlayer spaces of clay minerals, forcing the layers apart and resulting in soil expansion. Conversely, during dry conditions, water evaporates from these interlayer spaces, causing the layers to contract and the soil to shrink. This shrink–swell cycle may repeat several times depending on environmental conditions, leading to considerable ground movement.

The magnitude of swelling depends on several factors, including:

Mineralogical composition: Soils with higher montmorillonite content exhibit greater volume changes.

Moisture variation: Seasonal rainfall, irrigation practices, and groundwater fluctuations strongly influence swelling behavior.

Soil structure and density: Loose or poorly compacted soils tend to swell more than dense, well-compacted soils.

Environmental conditions: Temperature variation and evaporation rates can accelerate shrink–swell cycles.

Expansive soils are widely distributed around the world, including regions of North America, Europe, and Algeria. They represent one of the most challenging geotechnical hazards due to their potential to cause long-term structural damage. Consequently, proper identification, testing, and management of expansive soils are essential in civil engineering design and construction practices [1].



Figure 1.1: Illustration of soil swelling and shrinkage behavior [1]

1.3 Mineral Composition of Swelling Soils

The mineralogical composition of expansive soils is a primary factor governing their swelling and shrinkage behavior. These soils are typically rich in clay minerals, while their volume change characteristics are predominantly controlled by the presence of specific clay minerals that interact strongly with water. Among these, montmorillonite and other smectite-group minerals play a dominant role due to their layered structure, which allows water molecules to enter between layers and cause significant expansion.

In addition to smectites, expansive soils often contain kaolinite and illite. Kaolinite exhibits a relatively stable and compact structure with low swelling potential, whereas illite shows moderate swelling behavior. Non-clay minerals such as quartz and other silicates are also commonly present and form part of the coarse-grained fraction. Although these minerals do not directly contribute to swelling, they influence soil texture and mechanical stability.

The relative proportions of smectite-group minerals and non-expansive minerals strongly affect the soil's cation exchange capacity (CEC), plasticity, and susceptibility to volume changes under varying moisture conditions. Typical mineralogical compositions reported in geotechnical literature indicate that montmorillonite content may range from approximately 20% to 50%, with illite and kaolinite present in smaller proportions, while non-clay minerals such as quartz constitute a significant fraction of the remaining material [2].

Clay Mineral Structures

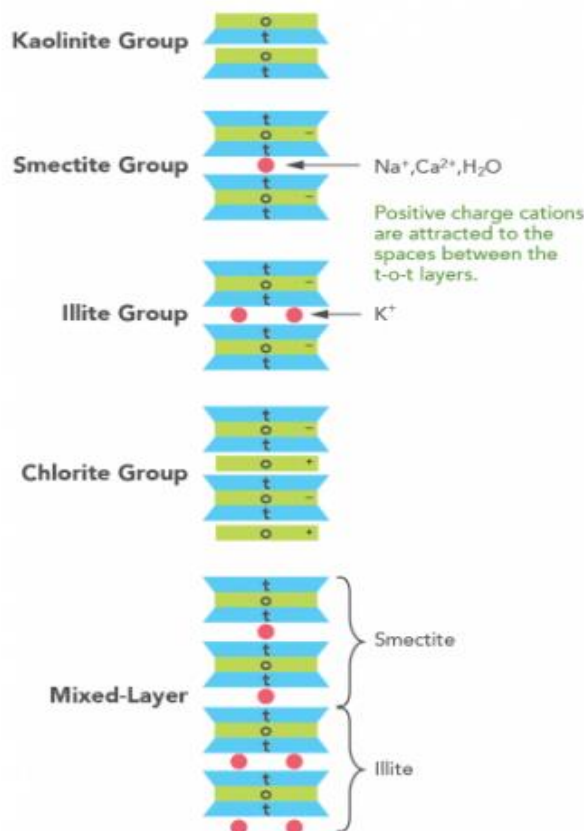


Figure 1.2. Clay mineral structure in expansive soils [4]

Table 1.1. Mineralogical Composition of Expansive Soils [10]

Effect on Soil Behavior	Swelling Potential	Mineral Group	Mineral
High plasticity, high water absorption	Very High	Smectite	Montmorillonite
Strong swelling–shrinkage behavior	High	Smectitegroup	Smectite
Moderate plasticity and limited swelling	Moderate	Illite	Illite
Stable behavior, low plasticity	low	Kaolinite	Kaolinite

1.4 Physical and Mechanical Properties of Expansive Soils

Expansive soils exhibit distinct physical and mechanical properties that are closely linked to their high clay content and mineralogical composition. According to Benramdane et al. (1995), expansive soils in Algeria are generally characterized by a high proportion of fine clay particles, which significantly influence their behavior. These soils typically exhibit high liquid limits and plasticity indices, indicating strong sensitivity to changes in water content.

From a physical perspective, expansive soils demonstrate high water absorption capacity, resulting in considerable volume changes. Their free swell potential may reach high values, rendering them unsuitable for construction without prior treatment. Moreover, their moisture–density relationship is characterized by high optimum moisture content and relatively low maximum dry density, reflecting their fine-grained nature and affinity for water.

From a mechanical standpoint, expansive soils are known for low shear strength and high compressibility, particularly under saturated conditions. Benramdane et al. (1995) reported that increasing water content leads to a significant reduction in mechanical strength. In confined conditions, these soils can develop swelling pressure capable of exerting substantial stresses on foundations and pavements. This behavior explains the frequent occurrence of cracks, heaving, and structural damage observed in civil engineering works founded on expansive soils in several regions of Algeria [4].

Table 1.2. Physical properties of expansive soils. [3]

Properties	S1	S2	S3	S4	S5	S6
------------	----	----	----	----	----	----

Free Swell Index, FSI (%)	49	51	71	99	145	171
Atterberg's limits						
Liquid limit (%)	52	54	60	64	72	79
Plastic limit (%)	24	27	31	33	35	38
Plasticity Index (%)	28	27	29	31	37	41
Standard Proctor						
Optimum moisture content (%)	19	20.2	21	22	24	25
Maximum dry density (kN/m ³)	1.54	1.51	1.47	1.45	1.43	1.41

1.5 Swelling Mechanism

The swelling mechanism of expansive soils is mainly attributed to their mineralogical composition, particularly the presence of expansive clay minerals such as montmorillonite. According to Benramdane et al. (1995), the swelling phenomenon occurs as a result of water infiltration into the clay structure, leading to an increase in soil volume.

At the microscopic scale, swelling is governed by the interaction between water molecules and clay particles. When water penetrates the soil, it is absorbed by the clay minerals and enters the interlayer spaces of the crystal lattice. This process causes an increase in the distance between clay layers, resulting in a macroscopic volume expansion of the soil mass. The higher the clay content and specific surface area, the greater the swelling potential.

Another important mechanism involved in soil swelling is cation exchange. Expansive clays possess negatively charged surfaces that attract exchangeable cations (such as Na⁺, Ca²⁺). Benramdane et al. (1995) highlighted that soils rich in sodium ions exhibit a higher swelling capacity compared to calcium-dominated soils, due to the weaker bonding forces between particles in sodium clays.

Swelling can occur under free conditions, where the soil is allowed to expand freely, or under confined conditions, where the expansion is restrained by structural loads. In the latter case, the soil develops a swelling pressure, which can generate significant stresses on foundations and pavements. This pressure is one of the main causes of structural damage observed in constructions built on expansive soils in several regions of Algeria.

In summary, the swelling mechanism of expansive soils is a combined result of water absorption, mineralogical structure, and physicochemical interactions, which explains the complex and harmful behavior of these soils in geotechnical engineering applications.[5]

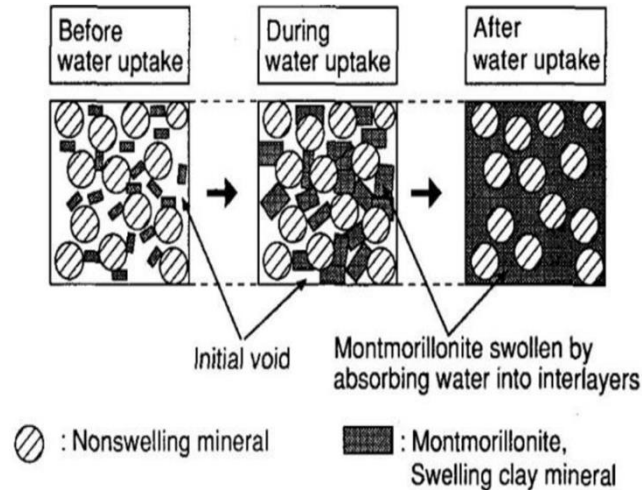


Figure 1.3. Mechanism on the swelling pressure of expansive soil [6]

1.6 Problems in Geotechnical Engineering

Expansive soils cause significant engineering problems due to their tendency to undergo large volume changes (swelling when wet and shrinking when dry). These cyclic movements generate stresses that affect structures and infrastructure built on or within the soil zone affected by moisture changes.

Expansive soils can cause:

- **Differential Movement and Structural Damage**
- **Mechanics of Movement:** When moisture levels fluctuate, expansive soils can swell significantly, leading to uneven displacement. This differential movement can severely compromise the integrity of structures.
- **Impact on Structures:** Cracks may appear in various parts of buildings, such as foundations, walls, and floors. Over time, these cracks can widen and lead to structural failure if not properly addressed.
- **Mitigation Strategies:** Engineers often use techniques like deep foundations, moisture barriers, or soil stabilization methods to reduce the impact of differential movement.
- **Uplift and Settlement of Foundations**
- **Mechanisms of Uplift and Settlement:** During periods of wet weather, expansive soils can exert upward pressure on foundations, particularly those that are shallow or lightly designed. Conversely, during dry periods, the soil shrinks, which can lead to settlement.

- **Consequences:** This cyclical behavior can distort load-bearing elements, leading to uneven floors and misaligned door frames. In severe cases, it may necessitate extensive repairs or even rebuilding of affected structures.
- **Design Considerations:** Engineers often need to design foundations that can accommodate potential movements, including using reinforced concrete or deep pilings that extend into more stable soil layers.
- **Damage to Pavements and Roads**
- **Effects on Pavements:** Expansive soils can lead to significant problems for roadways and pavements. Heaving and cracking due to soil expansion can result in dangerous driving conditions and increased maintenance costs.
- **Maintenance Challenges:** Regular repairs may be needed to address surface irregularities, which can disrupt traffic and lead to economic losses.
- **Preventive Measures:** To mitigate these issues, engineers can employ techniques such as proper drainage systems, flexible pavement materials, or even soil replacement to improve subgrade conditions.
- **Lateral Thrust on Walls and Structures**
- **Nature of Lateral Pressure:** As expansive soils swell, they can exert considerable horizontal pressure against basement and retaining walls. This pressure can lead to structural failure if the walls are not adequately reinforced.
- **Potential for Damage:** Walls may bow, crack, or deform under this lateral thrust, compromising not only the wall itself but also the stability of adjacent structures.
- **Reinforcement Techniques:** Engineers may use techniques such as tiebacks, anchors, or increased wall thickness to counteract these forces and ensure structural integrity.
- **Slope Instability and Soil Movement**
- **Risk of Landslides:** In sloped areas with expansive soils, moisture variations can lead to slope instability. The weight of the soil combined with moisture-induced swelling can trigger landslides or creep.
- **Implications for Construction:** This instability poses risks not just to structures on the slope but also to those below it, necessitating careful site assessment and design.
- **Stabilization Solutions:** Engineers may implement retaining walls, drainage systems, and vegetation to stabilize slopes and mitigate the effects of expansive soils.[7]



Figure 1.4: Examples of structural damage caused by swelling soils. [8]

1.7 Traditional Treatment Methods

Traditional treatment methods for expansive soils have long been integral to geotechnical engineering practice due to their effectiveness in controlling volume change behavior and improving soil engineering performance. Expansive soils are characterized by high plasticity and significant swell–shrink behavior resulting from the presence of active clay minerals such as montmorillonite and illite. These soils undergo volumetric changes when exposed to moisture fluctuations, which can cause severe damage to pavements, foundations, retaining structures, and underground utilities.

To mitigate these problems, conventional soil stabilization techniques focus on chemical modification of soil mineralogy and structure using calcium-based additives. The primary objective of these treatments is to reduce soil plasticity, suppress swelling pressure, improve strength parameters, and enhance durability under cyclic wetting and drying conditions.

1.7.1 Mechanisms of Traditional Chemical Stabilization

The effectiveness of traditional stabilizers such as lime, cement, and fly ash is attributed to a series of physicochemical processes:

1. Cation Exchange

Calcium ions (Ca^{2+}) from stabilizers replace monovalent ions (Na^+ , K^+) adsorbed on clay particle surfaces. This reduces electrostatic repulsion between particles, leading to a more stable soil structure.

2. Flocculation and Agglomeration

Clay particles rearrange from a dispersed orientation to a flocculated structure, resulting in increased particle size, reduced plasticity, and improved workability.

3. Pozzolanic Reactions

Calcium reacts with amorphous silica and alumina present in clay minerals to form cementitious compounds such as calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH). These reactions are time-dependent and contribute to long-term strength gain.

4. Cementation

The formation of binding compounds creates a rigid matrix that improves stiffness, strength, and resistance to moisture-induced deformation.

Through these mechanisms, traditional stabilizers fundamentally alter the soil fabric, transforming weak, moisture-sensitive clays into stronger and more durable materials suitable for engineering applications.

1.7.2 Lime Stabilization

Lime stabilization is particularly effective for highly plastic expansive clays. Hydrated lime ($\text{Ca}(\text{OH})_2$) or quicklime (CaO) is commonly used depending on field conditions.

a. Immediate Effects

- Reduction in plasticity index
- Improvement in workability
- Decrease in soil cohesion due to flocculation
- Lower moisture susceptibility

b. Long-Term Effects

- Formation of CSH and CAH compounds
- Increased unconfined compressive strength
- Reduced swell potential and swelling pressure
- Enhanced durability under environmental loading

Lime-treated soils often exhibit improved resistance to cyclic wetting and drying, making this method suitable for subgrades, embankments, and lightly loaded foundations. However, lime stabilization may be less effective in soils with low clay content or insufficient reactive silica and alumina.

c. Limitations of Lime Stabilization

- Requires adequate curing time
- Performance affected by sulfate presence (risk of ettringite formation)

- Less effective in organic or sandy soils

1.7.3 Cement Stabilization

Cement stabilization relies on the hydration of Portland cement to form a strong soil–cement composite.

Unlike lime, cement hydration reactions occur rapidly and produce immediate strength gains.

a. Engineering Benefits

- Significant increase in compressive and shear strength
- Improved stiffness and load-bearing capacity
- Reduced compressibility and permeability
- Enhanced resistance to erosion and weathering

Cement-treated expansive soils are widely used in **road bases, airport pavements, industrial floors, and heavy structural foundations**, where high strength and low deformation are critical.

b. Limitations of Cement Stabilization

- Higher material and construction costs
- Increased brittleness compared to lime-treated soils
- Higher carbon footprint due to cement production
- Potential cracking under shrinkage if not properly designed

1.7.4 Fly Ash and Supplementary Additives

Fly ash is commonly classified into **Class C (high calcium)** and **Class F (low calcium)** fly ash. Both types can be used to stabilize expansive soils, often in combination with lime or cement.

a. Role of Fly Ash

- Acts as a pozzolanic material
- Enhances strength development
- Reduces plasticity and swelling potential
- Improves workability and compaction characteristics

The use of fly ash contributes to **waste recycling and cost reduction**, making it an attractive option in large-scale projects. Other traditional additives such as gypsum, bitumen, and salts have been applied in specific scenarios, though their usage is less common today due to durability and environmental concerns.

[9]

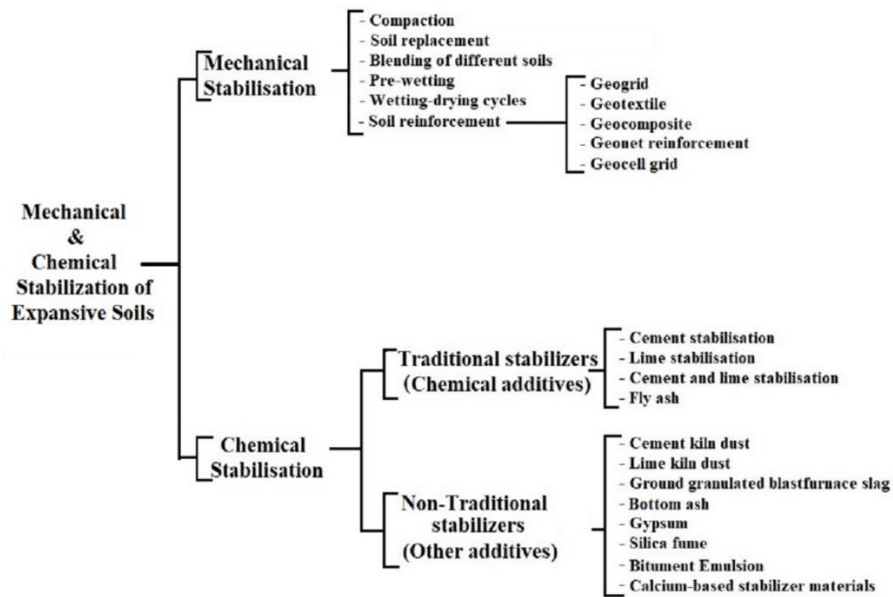


Figure 1.5: Mechanical and Chemical Stabilizations methods of expansive soils. [9]

Table 1.3: Conventional Treatment Methods for Expansive Soils [10]

Treatment Method	Materials Used	Effect on Expansive Soils	Limitations
Lime Stabilization	Hydrated lime (Ca(OH) ₂), Quicklime (CaO)	Reduces plasticity, swelling potential, and swelling pressure; improves strength	Ineffective in sulfate-rich soils; requires curing time
Cement Stabilization	Ordinary Portland Cement (OPC)	Increases strength and stiffness; reduces compressibility and swelling	High cost; high CO ₂ emissions; brittle behavior
Fly Ash Stabilization	Class C / Class F fly ash	Reduces plasticity and swelling; improves workability	Requires activators (lime/cement) for low-calcium ash
Lime–Fly Ash Mixture	Lime + fly ash	Improved strength and reduced swell compared to lime alone	Performance depends on material quality

1.8 Global Distribution of Expansive Soils

Expansive soils Understanding their global distribution is crucial for planning, risk assessment, and soil stabilization strategies.

1.8.1 Worldwide Occurrence

Expansive soils occur in all continents, but they are especially prevalent in arid and semi-arid regions. The main controlling factors are:

- . **Geology:** Areas with clay-rich sedimentary formations or volcanic ash deposits often contain high proportions of swelling clays such as montmorillonite.
- . **Climate:** Regions with alternating wet and dry seasons experience repeated soil expansion and contraction, increasing the potential for ground heave and structural stress.
- . **Hydrology:** Poorly drained areas, low rainfall zones, and regions with shallow groundwater tables influence soil moisture cycles and swelling behavior.

. **Geomorphology:** Low-lying plains, river basins, and alluvial deposits are typical zones where expansive soils are concentrated.

1.8.2 Regional Examples

Expansive soils have been documented in more than 40 countries worldwide, affecting both developing and developed nations. Representative examples include:

Africa: Ethiopia, Ghana, Kenya, Morocco, South Africa, Zimbabwe, Algeria. In these countries, expansive soils are commonly found in semi-arid highlands and along river valleys.

Asia: China, India, Iran, Israel, Japan, Oman. In China and India, expansive clays cover vast regions affecting rural and urban construction.

The Americas: United States, Canada, Mexico, Argentina, Cuba, Venezuela. In the USA, Texas, Oklahoma, and parts of California are well-known for extensive clay soils that swell during rainfall.

Europe: Spain, Greece, Turkey, UK. In southern Europe, clay-rich soils in Mediterranean climates are subject to seasonal wetting and drying, causing infrastructure challenges.

Oceania: Australia. Expansive soils are widespread across New South Wales, Victoria, and Western Australia, where low rainfall and high evaporation cycles intensify soil movement.

1.8.3 Climatic Influence on Distribution

Expansive soils are particularly sensitive to climatic conditions:

Arid and semi-arid climates amplify the swelling potential due to high evaporation rates and intermittent rainfall.

Tropical and temperate climates may still have expansive soils, especially where high-plasticity clays are present, but the behavior is less severe compared to semi-arid regions.

Seasonal moisture variations create cyclic swelling and shrinkage, which leads to long-term damage to foundations if not properly addressed.

1.8.4 Engineering and Socioeconomic Impacts

The global distribution of expansive soils has direct implications for civil engineering and infrastructure planning:

Structural damage: Cracks in walls, floors, and foundations, differential settlement, and heaving pavements.

Pipeline deformation: Buried utilities can bend or break due to soil movement.

Road maintenance: Roads on expansive soils require frequent repair due to potholes and uneven surfaces.

Economic burden: Countries with extensive expansive soils face higher construction and maintenance costs. For instance, in the USA and Australia, billions of dollars are spent annually to repair structures affected by soil heave.

Planning measures: Accurate mapping and understanding of global distribution help engineers select appropriate mitigation techniques such as soil stabilization, moisture control, and foundation design adaptations. [10]

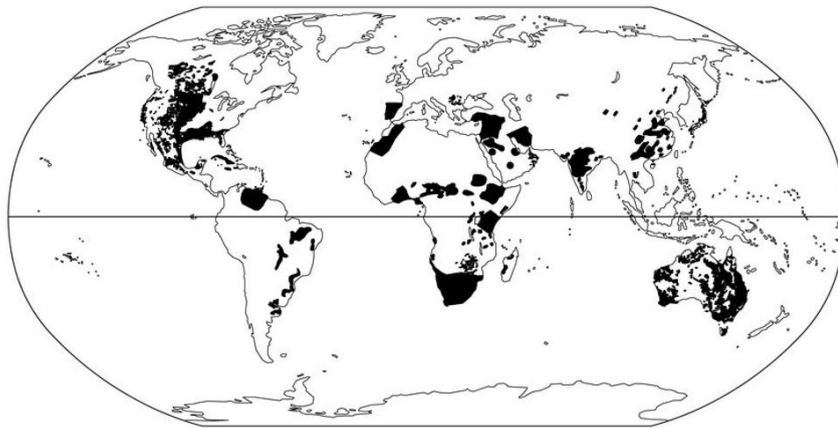


Figure 1.6: Global Distribution of Reported Expansive Soil Sites (Nelson et al., 2015). [11]

1.9 Conclusion

Expansive soils are primarily characterized by their sensitivity to moisture variations, resulting in cyclic swelling and shrinkage that can generate substantial ground movements. These behaviors are largely controlled by mineralogical composition, particularly the presence of smectite-group clay minerals such as montmorillonite, which exhibit high water absorption capacity and strong physicochemical interactions. The physical and mechanical properties of expansive soils, including high plasticity, low shear strength under saturated conditions, and significant swelling pressure, make them particularly problematic for civil engineering structures. The swelling mechanism, driven by water infiltration, interlayer expansion, and cation exchange processes, explains the development of both free swell and confined swelling pressures that can adversely affect foundations, pavements, retaining structures, and slopes. Numerous geotechnical problems such as differential movement, uplift, settlement, lateral thrust, and slope instability have been identified as direct consequences of these behaviors.

Traditional treatment methods, including lime, cement, and fly ash stabilization, were reviewed as widely adopted solutions for mitigating the adverse effects of expansive soils. While these methods can significantly improve soil performance by reducing plasticity and swelling potential and increasing strength, they also present limitations related to cost, environmental impact, and material compatibility. Furthermore, the global distribution of expansive soils highlights their prevalence across diverse climatic and geological settings, underscoring the substantial economic and engineering challenges they pose worldwide.

In conclusion, the complexity and severity of problems associated with expansive soils necessitate careful characterization, appropriate design strategies, and effective stabilization techniques.

Chapter 2

Geopolymer Binders for Soil Stabilization: Materials, Mechanisms, and Engineering Performance

2.1 Introduction

The stabilization of expansive soils represents a major challenge in geotechnical engineering due to their pronounced sensitivity to moisture variations and the resulting swell–shrink behavior. Conventional stabilization techniques, such as lime and ordinary Portland cement (OPC), have been widely applied to mitigate these problems by improving strength and reducing plasticity. However, the high carbon footprint, energy-intensive production processes, and durability concerns associated with traditional binders have motivated the search for more sustainable and durable alternatives.

In recent years, geopolymer binders—also known as alkali-activated materials—have emerged as a promising solution for soil stabilization applications. Geopolymers are inorganic binders synthesized through the alkaline activation of aluminosilicate-rich materials such as fly ash, ground granulated blast furnace slag, metakaolin, and volcanic ash. Unlike OPC, which relies on hydration reactions involving calcium phases, geopolymers develop strength through geopolymerization, a process that forms a three-dimensional aluminosilicate network dominated by Si–O–Al bonds. This fundamental difference results in lower greenhouse gas emissions, reduced energy consumption, and enhanced chemical durability.

From a geotechnical perspective, geopolymers offer several advantages when applied to expansive soils. The geopolymer gel penetrates soil pores, binds particles into a dense matrix, reduces permeability, and alters clay mineral activity. These mechanisms contribute to significant reductions in plasticity, swelling potential, and swelling pressure, while simultaneously improving strength, stiffness, and long-term stability. Moreover, the ability to utilize industrial by-products as raw materials aligns geopolymer technology with sustainability and circular economy objectives.

2.2 Definition and background

A geopolymer is an inorganic binder formed through the alkaline activation of aluminosilicate materials, a concept first introduced and extensively developed by Davidovits. According to geopolymer theory, aluminosilicate precursors such as fly ash, metakaolin, or slag react with alkaline solutions to form a hardened material through a process known as geopolymerization. This process involves the dissolution of silica and alumina species in a highly alkaline environment, followed by their reorganization into a three-dimensional amorphous to semi-crystalline aluminosilicate network composed mainly of Si–O–Al bonds. The resulting structure provides the geopolymer with cement-like characteristics, including high mechanical strength and durability.

Unlike ordinary Portland cement, which gains strength through hydration reactions producing calcium silicate hydrates, geopolymers rely on a polymerization mechanism that does not depend on

calcium phases. This fundamental difference leads to lower energy consumption during production and significantly reduced carbon dioxide emissions. Davidovits emphasized that geopolymer materials can reduce CO₂ emissions by up to 60–80% compared to Portland cement, making them environmentally attractive binders for sustainable construction.

In geotechnical engineering, the application of geopolymers for soil stabilization has gained attention due to their ability to interact effectively with soil particles. When mixed with soil, the geopolymer gel penetrates the pore spaces and binds soil grains together, forming a rigid and dense matrix. This bonding mechanism improves interparticle cohesion and friction, resulting in increased shear strength and stiffness. Additionally, the geopolymer matrix limits water penetration and reduces the activity of clay minerals, which leads to a significant reduction in plasticity and swelling behavior, particularly in expansive soils.

Davidovits highlighted that the chemical stability and low permeability of geopolymer matrices contribute to enhanced long-term performance in aggressive environments. These properties make geopolymers suitable for soil improvement applications where durability, resistance to chemical attack, and dimensional stability are critical. Consequently, geopolymers represent a promising alternative to traditional stabilizers such as lime and cement, especially in the stabilization of problematic soils and the development of sustainable geotechnical solutions.

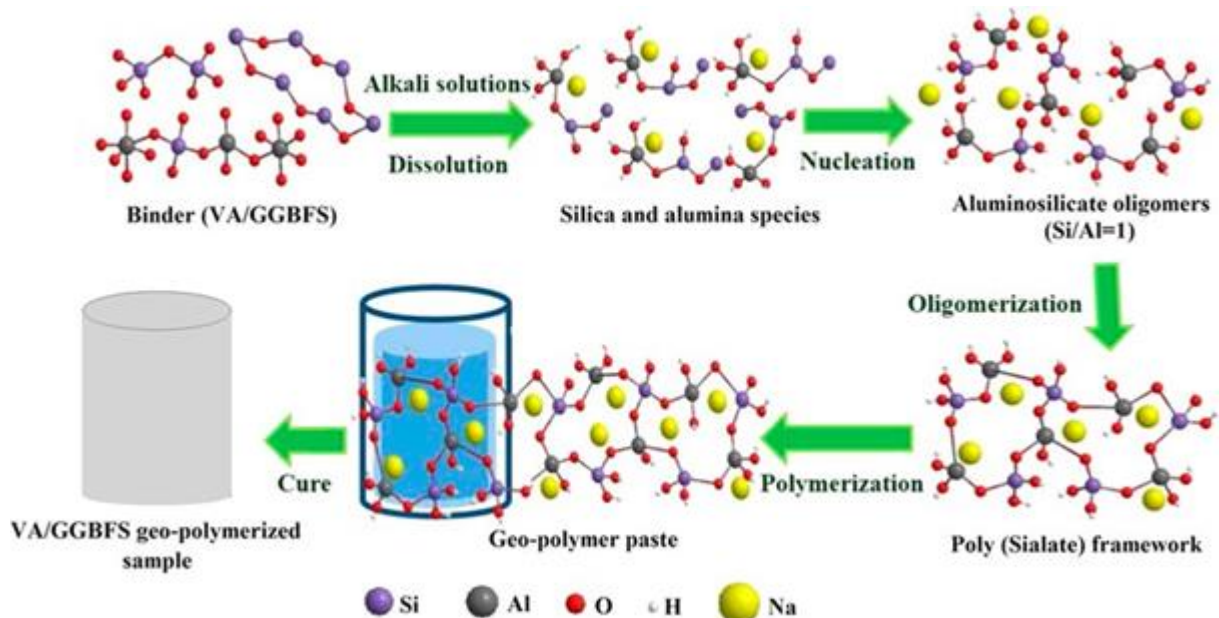


Figure 2.1: Schematic structure of geopolymer network

2.3 Raw Materials and Alkaline Activators

2.3.1 Aluminosilicate Raw Materials

The raw materials used in the synthesis of geopolymers are primarily aluminosilicate-rich substances, which supply the essential silicon (Si) and aluminum (Al) elements required for the geopolymerization process. These materials are typically derived from natural sources or industrial by-products and are selected based on their chemical composition and reactivity in alkaline environments. Common aluminosilicate precursors include fly ash, ground granulated blast furnace slag (GGBS), metakaolin, volcanic ash, and other silica-rich industrial wastes.

According to Davidovits, the effectiveness of a raw material in geopolymer synthesis depends largely on its ability to release reactive silica and alumina when exposed to alkaline solutions. Materials containing a high proportion of amorphous or glassy phases are particularly suitable, as these phases dissolve more readily than crystalline minerals. This dissolution is a critical first step in geopolymerization, as it enables the formation of aluminosilicate oligomers that later polymerize into a hardened binder.

The use of industrial by-products as raw materials provides not only technical benefits but also environmental advantages. By valorizing wastes such as fly ash and slag, geopolymer technology contributes to waste reduction and promotes sustainable construction practices. Davidovits emphasized that such materials are ideal geopolymer precursors due to their chemical composition, availability, and low environmental impact.

2.3.2 Chemical Composition and Reactivity of Raw Materials

The chemical composition of aluminosilicate precursors plays a decisive role in determining the reactivity and final performance of geopolymer binders. In particular, the proportions of silica (SiO_2) and alumina (Al_2O_3) strongly influence the geopolymer network structure. Davidovits highlighted the importance of the Si/Al atomic ratio, which controls the degree of polymerization, structural stability, and mechanical behavior of the resulting material.

Lower Si/Al ratios generally lead to rigid and highly cross-linked structures with high compressive strength and thermal stability, while higher ratios tend to produce more flexible networks with improved workability and crack resistance. Therefore, controlling the chemical composition of the raw materials allows the tailoring of geopolymer properties to meet specific engineering requirements.

In addition to major oxides, the presence of minor constituents such as calcium, iron, and magnesium can also affect geopolymerization. For example, calcium-rich precursors such as slag may contribute to the formation of additional binding phases, enhancing early strength development. However, excessive calcium content may alter the geopolymer mechanism and must be carefully controlled to maintain the integrity of the aluminosilicate network.

2.3.3 Physical Characteristics of Raw Materials

Beyond chemical composition, the physical characteristics of raw materials significantly influence geopolymer synthesis and performance. Key physical properties include particle size distribution, specific surface area, and degree of amorphousness. Finer particles with higher surface areas provide greater contact with alkaline activators, leading to faster dissolution and more efficient geopolymerization.

Davidovits noted that materials with high amorphous content are more reactive and yield geopolymers with superior mechanical properties. In contrast, highly crystalline materials exhibit limited reactivity and may require thermal or mechanical activation prior to use. Therefore, pre-treatment processes such as calcination (in the case of metakaolin) are often employed to enhance reactivity by transforming crystalline structures into amorphous phases.

These physical factors are particularly important in soil stabilization applications, where uniform mixing and effective interaction between the geopolymer binder and soil particles are essential for achieving consistent strength improvement.

2.3.4 Role of Raw Materials in Soil Stabilization

When geopolymers are applied as soil stabilizers, the aluminosilicate raw materials play a dual role. First, they act as precursors for the geopolymer binder, forming a hardened matrix upon activation. Second, they interact physically and chemically with soil particles, enhancing the overall structure of the treated soil.

The geopolymer gel formed during activation penetrates the pore spaces between soil grains and creates strong interparticle bonds. This results in a dense and cohesive soil–binder matrix that exhibits increased shear strength, stiffness, and load-bearing capacity. Davidovits emphasized that this chemical bonding mechanism provides greater long-term stability compared to traditional stabilization methods based on cement or lime.

Furthermore, the geopolymer matrix reduces soil permeability and limits moisture ingress, which is particularly beneficial for expansive soils. By restricting water movement and clay mineral activity, geopolymer stabilization effectively reduces swelling, shrinkage, and plasticity.

2.3.5 Alkaline Activators in Geopolymer Synthesis

Alkaline activators are a fundamental component of geopolymer systems, as they initiate and sustain the geopolymerization process. Their primary function is to create a highly alkaline environment that promotes the dissolution of silica and alumina from the solid precursors. The most commonly used alkaline activators are sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃).

Sodium hydroxide serves as the main source of hydroxyl ions (OH⁻), which attack the aluminosilicate structure of the raw materials and break the Si–O–Si and Si–O–Al bonds. This process releases soluble silicate and aluminate species into the solution, enabling subsequent polymerization reactions. Davidovits stressed that sufficient alkalinity is essential to ensure effective dissolution and gel formation.

Sodium silicate, on the other hand, supplies additional soluble silica, which enhances the polymerization process and improves the mechanical properties of the geopolymer. The presence of soluble silicate accelerates gel formation and contributes to the development of a more homogeneous and dense aluminosilicate network.

2.3.6 Influence of Activator Concentration and Ratios

The concentration and proportion of alkaline activators have a direct impact on the kinetics of geopolymerization and the properties of the final binder. Increasing the concentration of sodium hydroxide generally enhances dissolution and accelerates strength development. However, excessively high concentrations may lead to rapid setting, increased brittleness, and reduced long-term durability.

The ratio between sodium silicate and sodium hydroxide solutions is equally important. An optimal balance ensures adequate dissolution while promoting efficient polymerization. Davidovits pointed out that improper ratios may result in incomplete reactions or weak geopolymer structures. Therefore, careful optimization of activator composition is necessary, especially for geotechnical applications where durability and mechanical stability are critical. [12]

Table 2.1: RAW MATERIALS AND ALKALINE ACTIVATORS USED IN GEOPOLYMERS.

[12]

Type	Material	Source / Origin
Raw Materials	Fly Ash	Coal combustion by-product
	GGBFS	Iron and steel industry by-product
	Volcanic Ash	Natural pozzolanic material
Alkaline Activators	Potassium Hydroxide (KOH)	Chemical reagent
	Sodium Silicate (Na ₂ SiO ₃)	Commercial alkaline solution

2.4 Geopolymerization Mechanism

The term geopolymerization describes the series of chemical reactions that transform aluminosilicate materials into a hardened inorganic polymer with a three-dimensional network of Si–O–Al bonds. This mechanism is fundamentally different from the hydration reactions in Portland cement, which are dominated by calcium silicate hydrates. In geopolymer systems, the aluminosilicate precursors dissolve under alkaline conditions and reorder into an amorphous to semi-crystalline aluminosilicate matrix. The efficiency of geopolymerization directly controls the physical integrity and mechanical performance of the final material. Understanding this mechanism is therefore central to optimizing geopolymer formulations for engineering applications such as soil stabilization, concrete replacement, containment systems, and thermal insulation. [12]

2.4.1 Alkaline Activation: Creating a Reactive Environment

The mechanism of geopolymerization begins with the introduction of alkaline activators, most commonly sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃), to the aluminosilicate precursor. These activators drastically increase the pH of the system, often above 12–13, creating an environment that is highly effective at dissolving the fundamental building blocks of the precursor material. The extreme alkalinity encourages the breakdown of strong Si–O–Si and Si–O–Al bonds that are otherwise stable in the solid phase. The relative proportions and concentrations of NaOH and Na₂SiO₃ influence the solution’s alkalinity and its ability to dissolve reactive species. Sodium hydroxide primarily facilitates the breakdown of the aluminosilicate network, while sodium silicate contributes both alkalinity and additional soluble silica. The presence of both components provides a balance between dissolution and polymer network formation, which is crucial for high-performance geopolymer binders. [12]

2.4.2 Dissolution of Aluminosilicate Precursors

Once a highly alkaline environment is established, the solid precursor begins to dissolve. The dissolution process is a chemical reaction in which the aluminosilicate structure of the raw material breaks down into soluble silicate and aluminate species. The degree to which this occurs depends on the precursor's mineralogy. Materials with high amorphous content, such as fly ash or thermally activated metakaolin, are more reactive and dissolve readily. Crystalline phases, by contrast, dissolve slowly or may remain unreacted. The dissolution step releases monomeric SiO_4^{4-} and AlO_4^{5-} units into the activating solution. These monomers are the fundamental building blocks for subsequent polymerization reactions. The rate and extent of dissolution are critically influenced by particle size (smaller particles dissolve more quickly due to larger surface area), the activator's composition, temperature, and mixing conditions. Efficient dissolution ensures a high concentration of reactive species, which is essential for the development of a robust geopolymer matrix. [12]

2.4.3 Hydrolysis and Formation of Reactive Species

As dissolution progresses, silicate and aluminate monomers enter the solution and undergo hydrolysis, a process that alters their chemical state to form more reactive intermediates. In this stage, molecular reconfiguration occurs: Si–OH and Al–OH species form as water molecules interact with the dissolved ions. Hydrolysis increases the reactivity of the dissolved species by exposing under-coordinated silicon and aluminum atoms that are ready to form new covalent bonds. These reactive species serve as precursors for the polycondensation process. The balance between silicate and aluminate species in the pore solution also influences the ultimate chemical structure of the geopolymer network. A higher ratio of silicate species tends to increase cross-linking and network density, which generally enhances mechanical properties. By contrast, imbalanced ratios can lead to incomplete polymer networks, resulting in weaker and more porous materials. [12]

2.4.4 Polycondensation and Network Development

The heart of geopolymerization lies in polycondensation, a series of chemical reactions in which reactive silicate and aluminate species condense to form Si–O–Al and Si–O–Si bridges, eliminating small molecules such as water in the process. Polycondensation is a stepwise reaction that links monomeric and oligomeric species into larger polymeric chains and ultimately into a continuous three-dimensional framework. The evolving network can be viewed as a covalently bonded inorganic polymer gel. The development of this gel is central to the transition from a viscous, fluid mixture to a rigid, solid material. The structure of the network—its connectivity, cross-link density, and distribution of aluminum in tetrahedral coordination—determines key mechanical characteristics such as compressive strength, modulus of elasticity, and fracture resistance. The kinetics of polycondensation are influenced by factors including curing temperature, alkaline concentration, and precursor composition. Elevated temperatures accelerate the polycondensation reactions, promoting faster strength development and a more complete reaction at early ages. [12]

2.4.5 Gelation and Hardening

Following polycondensation, the newly formed inorganic polymer gel begins to harden. Gelation refers to the stage at which a mechanically coherent structure spans the entire volume of the material. As the gel matures, the interconnected network occupies pore spaces between unreacted particles and continues to densify. Hardening results from further condensation reactions and the reduction of free pore water as it becomes structurally bound within the gel. During this stage, physical changes such as shrinkage and pore refinement occur, contributing to increased mechanical strength. The microstructure evolves from a network of loosely bonded clusters to a densely cross-linked matrix. The extent of hardening and densification directly influences the geopolymer's performance characteristics, including its durability and resistance to environmental degradation. Proper curing conditions—such as controlled humidity and temperature—are essential to minimize cracking due to shrinkage and to promote uniform network development. [12]

2.4.6 Role of Alkali Ions and Water in Microstructure Development

Water and alkali ions play dual roles in the geopolymerization mechanism. Water acts as a medium for ion transport, facilitating the dissolution, hydrolysis, and polycondensation steps. Although water is not part of the final inorganic polymer structure, it influences the mobility of ionic species and the kinetics of chemical reactions. As polycondensation progresses, some of the water is expelled from the gel network, contributing to volumetric shrinkage. Meanwhile, alkali ions such as Na⁺ remain in the pore solution or become trapped within the geopolymer gel, balancing charge and affecting network stability. These cations also influence the pore structure and can modify properties such as ionic conductivity and chemical resistance. The distribution and mobility of water and alkali ions

contribute to the evolution of the pore system, which subsequently affects permeability, mechanical strength, and long-term durability. [12]

2.4.7 Microstructural Evolution and Defect Development

Microscopically, geopolymerization transforms an initially heterogeneous mixture of solid precursor particles and a liquid activator into a continuous solid network. Early in the process, unreacted precursor particles may act as filler phases embedded within a growing gel matrix. As polycondensation continues, the gel fills interstitial voids and envelops unreacted cores. Electron microscopy studies often show a dense, glassy gel surrounding residual particles, with the interface between reacted and unreacted zones becoming less distinct over time. However, defects such as microcracks, unreacted islands, and pore clusters can arise if dissolution is incomplete or if curing conditions are suboptimal. These microstructural defects act as stress concentrators under mechanical load and can adversely affect performance. By optimizing precursor reactivity, activator composition, and curing regime, practitioners can minimize defect formation and improve the continuity and integrity of the geopolymer network. [12]

2.4.8 Influence of Curing Conditions

Curing conditions such as temperature, humidity, and time significantly influence the geopolymerization mechanism and ultimate material properties. Elevated temperature curing accelerates dissolution and polycondensation, leading to higher early-age strength and more complete network development. At ambient temperatures, the reactions proceed more slowly, requiring longer curing times to achieve similar degrees of polymerization. Controlled humidity prevents rapid evaporation of pore water, which could lead to shrinkage cracking. In engineering practice, selecting appropriate curing protocols tailored to specific precursor materials and activator systems is crucial for achieving desired mechanical and durability performance. [12]

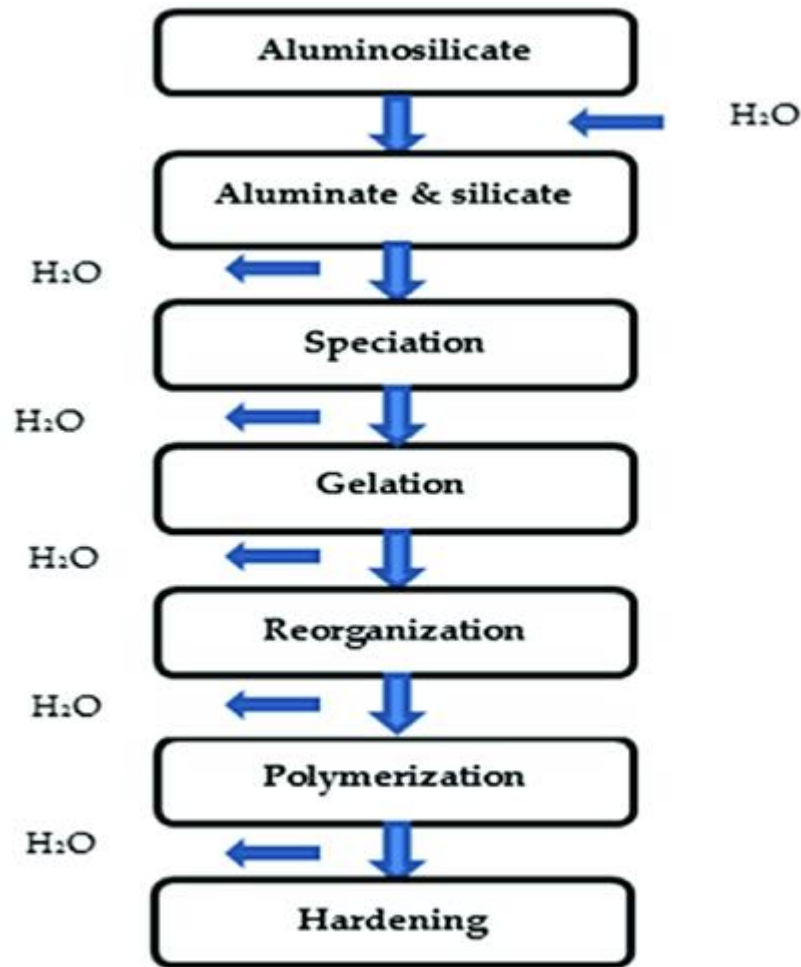


Figure 2.2: Process of Geopolymerization. [17]

2.5 Properties of Geopolymers

2.5.1 Introduction

Geopolymers are inorganic binder materials formed by the alkaline activation of aluminosilicate precursors such as fly ash, metakaolin, and slag. Their hardened structure consists of a three-dimensional network of Si–O–Al aluminosilicate bonds, giving them unique physical and mechanical characteristics compared to traditional Portland cement binders. These properties determine the performance of geopolymer materials in engineering applications, especially in construction and soil stabilization. The physical behaviour, mechanical strengths, and durability are influenced by the raw materials, mix design, activator systems, microstructure, and curing conditions. [13]

2.5.2 Physical Properties

a. Density

Density is a fundamental physical property indicating how compact the geopolymer material is. Higher density usually correlates with fewer voids and a more tightly packed solid network. Densities of geopolymer materials can vary widely depending on raw material types and mix formulation—for example, lightweight geopolymers with lower density ($\sim 1.0\text{--}1.6\text{ g/cm}^3$) can be produced for insulation applications, whereas highly dense, structural geopolymers may reach densities close to traditional concretes. [14]

A higher density generally improves mechanical strength and resistance to environmental factors; dense matrices restrict water penetration and increase load-bearing capacity, which is important for both construction and soil stabilization applications.

b. Porosity and Pore Structure

Porosity refers to the volume fraction of voids within the hardened geopolymer. It significantly affects mechanical performance and transport properties such as permeability and water absorption. Low porosity is associated with:

Higher strength due to reduced stress concentrations

Lower permeability, improving durability

Reduced water absorption, limiting moisture-related degradation

Conversely, higher porosity often results in reduced mechanical performance and increased susceptibility to environmental effects. Studies indicate that manipulating the pore structure through processing methods (e.g., pressing vs. foaming) can tailor geopolymer properties for specific applications, including acoustic insulation or structural performance.

[15]

c. Permeability and Water Absorption

Permeability measures how easily fluids can move through the geopolymer's pore network. Lower permeability is desirable in soil stabilization because it limits moisture movement, which can reduce swelling and shrinkage, and prevents aggressive agents from entering the matrix. Water absorption is closely related to porosity and provides insight into the interconnected nature of the pores. Well-densified geopolymers typically exhibit lower permeability and water uptake, contributing to long-term performance in aggressive environments. [16]

2.5.3 Mechanical Properties

a. Compressive Strength

Compressive strength is the most frequently tested mechanical parameter for geopolymer materials and is a primary indicator of load-bearing performance. Geopolymers often exhibit higher compressive strengths compared to ordinary Portland cement (OPC) concrete:

Typical geopolymer concrete (GPC) shows compressive strengths ranging from 60 to over 100 MPa depending on the mix design, curing conditions, and raw materials.

Strength development continues with age due to ongoing geopolymerization reactions, and heat curing can further enhance strength gains, particularly at early ages.

The dense aluminosilicate gel network (commonly referred to as N-A-S-H gel in fly ash systems) is responsible for transferring loads and resisting deformation, making geopolymer binders suitable for high-strength applications in construction and soil stabilization. [13]

b. Flexural and Tensile Strength

While compressive strength reflects load-bearing capacity under compression, flexural strength indicates resistance to bending and cracking. Flexural performance is influenced by the quality of the geopolymer matrix and the presence of fibers or other reinforcing phases. Geopolymers can be reinforced with fibers such as polypropylene or basalt to significantly enhance tensile and flexural strengths, providing improved ductility and crack resistance compared to unreinforced mixes.

c. Elastic Modulus and Stiffness

The elastic modulus of a geopolymer material reflects its stiffness—how much it deforms elastically under stress. High elastic modulus is generally desirable in structural and geotechnical applications because it means the material will deform less under load. Geopolymers often exhibit high stiffness due to the rigidity of the aluminosilicate network, though the exact values depend on factors like porosity, raw material composition, and curing regime. Properly designed geopolymers can rival or exceed the stiffness of traditional cementitious materials. [16]

2.5.4 Microstructure and Mechanical Performance

Microstructure plays a key role in determining mechanical behaviour. Scanning electron microscopy (SEM) studies reveal that geopolymer binders consist of a dense gel matrix with embedded unreacted precursor particles. A well-formed gel network with minimal microcracks and low porosity improves load transfer and strength. The presence of unreacted particles, microcracks, or large pores can hinder performance by acting as stress concentrators. [13]

Microstructural refinement using nano-silica or other additives has been shown to enhance matrix densification, reduce pore size, and improve early-age strength by filling microvoids and refining the gel network.

2.5.5 Durability and Long-Term Performance

Durability encompasses resistance to chemical, thermal, and environmental degradation. Geopolymers generally demonstrate excellent durability characteristics:

- **Chemical resistance:** Geopolymers are highly resistant to acid and sulfate attack due to their aluminosilicate framework, which contains fewer calcium hydroxide phases susceptible to chemical attack compared to OPC binders.
- **Thermal stability**
- **Permeability and transport properties:** Low permeability and dense matrix formation enhance resistance against chloride ingress and other aggressive agents, which is critical for long-term durability. [16]

2.6 Interaction with Swelling Soils

Expansive soils are fine-grained soils that exhibit significant volume changes in response to moisture variation, a behavior closely associated with their mineralogical composition. Clays rich in layer silicate minerals such as montmorillonite and smectite possess a high capacity to absorb water within their interlayer structure due to electrostatic and hydration forces, leading to dramatic swelling when moisture increases and shrinkage when moisture decreases. These shrink–swell cycles can induce severe ground movements, causing differential settlement, heaving of pavements and foundations, cracking of structural elements, and reduced long-term performance of infrastructure if not properly mitigated. [18]

Conventional stabilization methods such as lime and ordinary Portland cement (OPC) have been widely employed to mitigate swelling behavior, largely through pozzolanic and hydration reactions that form cementitious products (e.g., calcium silicate hydrates) that bind soil particles and reduce plasticity. However, environmental concerns related to CO₂ emissions and long-term durability limitations have motivated research into more sustainable alternatives. One promising direction is the use of alkali-activated binders and geopolymers derived from industrial by-products, which can improve the geotechnical performance of expansive soils while reducing environmental impact. [18]

Table 2.2: Mechanical and Physical Properties of Geopolymers. [12]

Property Type	Property	Typical Range / Description
Mechanical Properties	Compressive Strength	20–80 MPa (can exceed 100 MPa with optimized mix)
	Tensile Strength	2–5 MPa
	Flexural Strength	4–10 MPa
	Elastic Modulus	10–40 GPa
Physical Properties	Density	1800–2400 kg/m ³
	Porosity	10–25 %
	Water Absorption	3–10 %
	Permeability	low
	Shrinkage	Very low compared to OPC

2.6.1 Reduction of Swelling Through Chemical and Physical Mechanisms

Research shows that geopolymer stabilization can significantly reduce the swelling potential and swelling pressure of expansive soils. A recent study on stabilizing expansive soils using geopolymer binders based on zeolitic tuff demonstrated that treated soils exhibited extremely low free swell percentages on the order of 0.25% compared to both untreated soils and those stabilized with OPC, highlighting a substantial reduction in volumetric expansion. This reduction in free swell percentage reflects how geopolymer interactions can limit water uptake and expansion pathways within the soil matrix. [19]

Geopolymer binders act through several complementary mechanisms

Cementitious Gel Formation: Alkali-activated aluminosilicate precursors (like fly ash or metakaolin) form amorphous to semi-crystalline aluminosilicate gels (e.g., N-A-S-H and C-(N)-A-S-H) that infiltrate soil pores, coat clay particles, and bind soil fabric into a cohesive matrix. These gels occupy void spaces that otherwise facilitate water ingress and clay expansion, effectively reducing the available space for volumetric growth. [19]

Cation Exchange and Diffuse Layer Compression: Clay particles in expansive soils are surrounded by a diffuse layer of exchangeable cations (e.g., Na⁺, Ca²⁺). Geopolymer activators introduce high alkalinity and ion concentrations, leading to a modification of the ionic environment. In some cases, divalent cations (such as Ca²⁺ released from calcium-rich precursors) replace monovalent cations on clay surfaces, compressing the electrical double layer and weakening the clay’s tendency to expand. [19]

Flocculation and Particle Aggregation: The chemical environment created by geopolymer binders encourages flocculation of clay particles. Aggregated particles form larger, more stable units that are

less susceptible to moisture-induced expansion. This flocculated structure also improves load transfer and shear resistance in treated soils. [19]

Together, these mechanisms contribute to a soil structure that is less reactive to moisture fluctuations, exhibiting lower plasticity and swelling behavior than untreated soils.

2.6.2 Microstructural Improvements and Pore Network Modification

The microstructure of expansive soils plays a crucial role in governing their swelling characteristics. Untreated expansive soils typically have a network of interconnected pores and capillaries that permit rapid water absorption, supporting swelling pressures as water ingress separates clay platelets. Geopolymer stabilization alters this microstructure by filling or bridging pore spaces with geopolymeric gels, which refine pore size distribution and reduce pore connectivity. The densification of the soil matrix achieved through gel infiltration can significantly diminish the pathways available for moisture migration, thereby reducing the soil's sensitivity to wetting and drying cycles. [19]

2.6.3 Strength and Engineering Performance Enhancements

Beyond swelling reduction, geopolymer-treated expansive soils typically exhibit enhanced mechanical properties such as increased unconfined compressive strength (UCS), improved stiffness, and greater bearing capacity. These improvements arise from the dual effects of chemical binding through geopolymer gel formation and physical reinforcement of soil structure via pore filling and particle aggregation. In some experimental cases, geopolymer mixes optimized for expansive soil treatment have shown marked reductions in swelling and shrinkage behavior alongside significant increases in strength compared to both untreated soils and soils stabilized with traditional binders. [20]

For example, research on fly ash-based geopolymer treatment demonstrated that optimized mixes (e.g., around 25% binder content) not only reduced free swell but also improved indices related to soil plasticity and strength, suggesting the feasibility of using such treatments in subgrade layers for flexible pavements and other infrastructure applications. [20]

2.6.4 Durability and Long-Term Stability

Durability considerations are essential when evaluating long-term performance of geopolymer-stabilized expansive soils, especially in environments subject to moisture cycles, wetting–drying, and sulfate exposure. A recent review of durability research indicates that geopolymer binders often outperform traditional lime/OPC stabilization under wetting–drying and sulfate attack due to the inherent chemical stability of aluminosilicate gels. While some high-calcium geopolymer systems may show vulnerabilities depending on composition, overall evidence suggests that geopolymer treatments enhance strength retention and reduce swelling over repeated environmental cycles when properly formulated. [21]

2.7 Advantages for Soil Improvement

The application of geopolymer technology for soil improvement offers a range of technical, environmental, and sustainability advantages compared to conventional soil stabilizers such as ordinary Portland cement (OPC) and lime. This section discusses these advantages in depth, based primarily on a comprehensive review of fly-ash-based geopolymers for soil stabilization with particular emphasis on clay soils. [22]

2.7.1 Superior Engineering Performance

One of the primary benefits of geopolymers in soil improvement is their ability to significantly enhance the mechanical properties of treated soils. Geopolymer binders, formed through the alkali activation of industrial aluminosilicate materials such as fly ash, slag, or metakaolin, produce cementitious gels that effectively bind soil particles. These gels interlock soil grains and fill interstitial voids, leading to improved structural integrity and load-bearing capacity. Research consistently shows that soils stabilized with geopolymer binders exhibit higher unconfined compressive strength (UCS) and improved stiffness compared to untreated soils, making them suitable for subgrade and subbase applications in road pavements and foundations. [22]

An important observation from the literature is that the strength enhancement often meets or exceeds the performance requirements specified in engineering standards. For example, geopolymer-treated clay soils can achieve UCS values comparable to or higher than those obtained with cement or lime stabilization, particularly when the precursor content, alkaline activator molarity, and curing conditions are properly optimized. [22]

2.7.2 Enhanced Durability and Microstructural Stability

Geopolymer binders also contribute to improved durability of treated soils under adverse environmental conditions. The aluminosilicate network formed during geopolymerization creates a dense, chemically stable matrix that is less susceptible to degradation from moisture cycles, sulfate attack, and aggressive soil environments. Unlike traditional OPC binders, which rely on calcium

silicate hydrates prone to leaching and chemical breakdown, geopolymer gels demonstrate higher resistance to acidic and sulfate environments, maintaining structural integrity over prolonged exposure. [22]

The microstructural enhancements imparted by geopolymerization—such as reduced porosity and refined pore size distribution—also reduce the permeability of treated soils. Lower permeability limits the ingress of water and harmful ions, thereby enhancing long-term stability and performance under cyclic wetting–drying conditions, which are typical in natural soil environments. [22]

Table 2.3: Comparison Between Untreated and Treated Expansive Soils. [9]

Property	Untreated Expansive Soil	Treated Expansive Soil
Plasticity Index (PI)	High	Reduced significantly
Swelling Potential	High to very high	Low to moderate
Swelling Pressure	High	Substantially reduced
Water Absorption	High	Reduced
Volume Change	Severe swell–shrink behaviour	Controlled and limited
Compressive Strength	Low	Increased
Soil Structure	Dispersed clay particles	Flocculated / cemented structure
Durability	Poor	Improved
Engineering Suitability	Problematic for foundations	Suitable for construction

2.7.3 Environmental Sustainability

A key advantage of geopolymer soil stabilization is its environmental performance compared to traditional binders. The production of Portland cement is associated with high energy consumption and significant CO₂ emissions, contributing to global greenhouse gas emissions. In contrast, geopolymers utilize industrial by-products—such as fly ash, blast furnace slag, and rice husk ash—that would otherwise require disposal, thus diverting waste from landfills and reducing the environmental burden of waste streams. [22]

The alkali activation of these waste materials forms a binder without requiring high-temperature clinker production, resulting in substantially lower carbon footprints and reduced energy demands. This environmental benefit aligns with global efforts to adopt sustainable materials in civil engineering and infrastructure developments. [22]

2.7.4 Economic and Resource Efficiency

In addition to technical and environmental benefits, geopolymer stabilization can offer economic advantages, particularly when locally available wastes are used as precursors. The use of industrial by-products such as fly ash or slag significantly reduces the need for virgin raw materials, lowering material procurement costs. Moreover, in many regions—including Algeria—such industrial wastes are abundant and inexpensive, providing a cost-effective alternative to imported or energy-intensive binders. [22]

While the cost of alkaline activators (e.g., sodium hydroxide and sodium silicate) remains a consideration, ongoing research focuses on optimizing activator dosages and mix designs to further reduce overall stabilization costs without compromising performance. [22]

2.7.5 Applicability Across Diverse Soil Types

Geopolymers exhibit versatility in application for stabilizing a wide range of problematic soils. Whether dealing with low-strength clays, silts, or even expansive and collapsible soils, geopolymer binders can be tailored by adjusting the precursor types, activator solutions, and curing regimes to address specific engineering challenges. Studies demonstrate that geopolymer stabilization can be effective across various soil mineralogies and moisture conditions, enhancing shear strength, reducing plasticity, and improving volumetric stability in treated soils.

This adaptability makes geopolymers attractive for applications such as roadway subgrades, embankments, foundation soils, and even in situ ground improvement where traditional stabilizers may be less effective or environmentally appropriate. [22]

2.7.6 Contribution to Circular Economy and Sustainability Goals

Geopolymer soil stabilization contributes to broader sustainability and circular economy objectives. By valorizing industrial waste, reducing reliance on traditional cementitious binders, and lowering greenhouse gas emissions, geopolymer technology supports sustainable construction practices. This alignment with environmental policies and sustainability frameworks enhances its attractiveness for infrastructure projects where regulatory and societal pressures favor greener solutions. [22]

2.8 Conclusion

Geopolymers, formed through the alkaline activation of aluminosilicate materials, represent a fundamentally different class of binders compared to conventional cementitious systems. Their strength development mechanism, based on geopolymerization rather than hydration, results in a dense and chemically stable aluminosilicate network that offers significant advantages in geotechnical applications.

The review of raw materials and alkaline activators highlighted the critical influence of precursor composition, reactivity, particle characteristics, and activator concentration on the geopolymerization

process and the resulting material properties. Understanding the geopolymerization mechanism—from alkaline activation and dissolution to polycondensation, gelation, and hardening—provides essential insight into how geopolymer binders develop their mechanical strength, durability, and microstructural integrity. These processes directly control the effectiveness of geopolymers when used as soil stabilizers.

The physical, mechanical, and durability properties of geopolymers demonstrate their suitability for soil improvement applications. High compressive strength, low permeability, reduced shrinkage, and excellent resistance to chemical attack contribute to superior long-term performance compared to traditional binders. When applied to expansive soils, geopolymers interact with clay minerals through gel formation, pore filling, cation exchange, and flocculation mechanisms. These interactions significantly reduce swelling potential and swelling pressure while enhancing strength, stiffness, and volumetric stability.

Furthermore, the environmental and economic advantages of geopolymer technology—such as reduced CO₂ emissions, utilization of industrial by-products, and alignment with circular economy principles—make geopolymers an attractive alternative for sustainable geotechnical engineering. Overall, this chapter establishes the scientific and engineering basis for using geopolymer binders in expansive soil stabilization. The concepts and mechanisms discussed herein provide the necessary framework for the experimental program and performance evaluation presented in the following chapters of this thesis.

Chapter 3

Materials, Experimental Program, and Methodology for Geopolymer Stabilization of Expansive Soil

.1 Introduction

The effective stabilization of expansive soils requires a thorough understanding of their intrinsic geotechnical properties as well as a carefully designed experimental methodology to evaluate improvement techniques. Laboratory-based investigations play a crucial role in quantifying the physical, chemical, and mechanical behavior of expansive clays and in assessing the efficiency of innovative stabilization approaches under controlled conditions. In this context, a rigorous experimental program is essential to establish reliable relationships between soil characteristics, treatment parameters, and resulting performance.

This chapter presents the materials and experimental methodology adopted to investigate the stabilization of an expansive clay soil using geopolymer binders derived from industrial by-products. The studied soil was collected from Jbel Dukkan, in the Tebessa region of northeastern Algeria, an area well known for the presence of highly expansive clay formations that pose serious challenges to civil engineering infrastructure. The experimental program was designed to characterize the natural soil, identify its swelling potential, and evaluate the effectiveness of geopolymer treatment based on Ground Granulated Blast Furnace Slag (GGBFS) and iron mine waste.

The chapter first describes the soil sampling procedure and site conditions, followed by a comprehensive geotechnical characterization of the natural soil through physical, chemical, and mechanical tests conducted in accordance with relevant standards. The obtained results are discussed to classify the soil and confirm its expansive nature. Subsequently, the geopolymer stabilization methodology is detailed, including the selection of materials, preparation procedures, binder dosages, mixing and compaction processes, and curing conditions. Finally, a comparative assessment of soil properties before and after geopolymer treatment is presented to highlight the effects of stabilization. This chapter establishes the experimental framework upon which the performance analysis and interpretation of results are based.

3.2 Soil Sampling and Site Description

A 100 kg sample of expansive soil was collected from Jbel Dukkan, Tebessa, northeastern Algeria, an area known for clay-rich layers prone to swelling and shrinkage. The site features exposed clay layers that crack when dry and become soft when wet, typical of highly expansive soils affecting civil engineering structures.

Samples were collected from the top 20–30 cm, air-dried, homogenized, and sieved in the laboratory to remove debris and prepare them for testing. This careful sampling ensures that the laboratory results accurately reflect the natural properties of the soil, providing a solid basis for studying improvement using GGBFS and iron mine waste geopolymers.

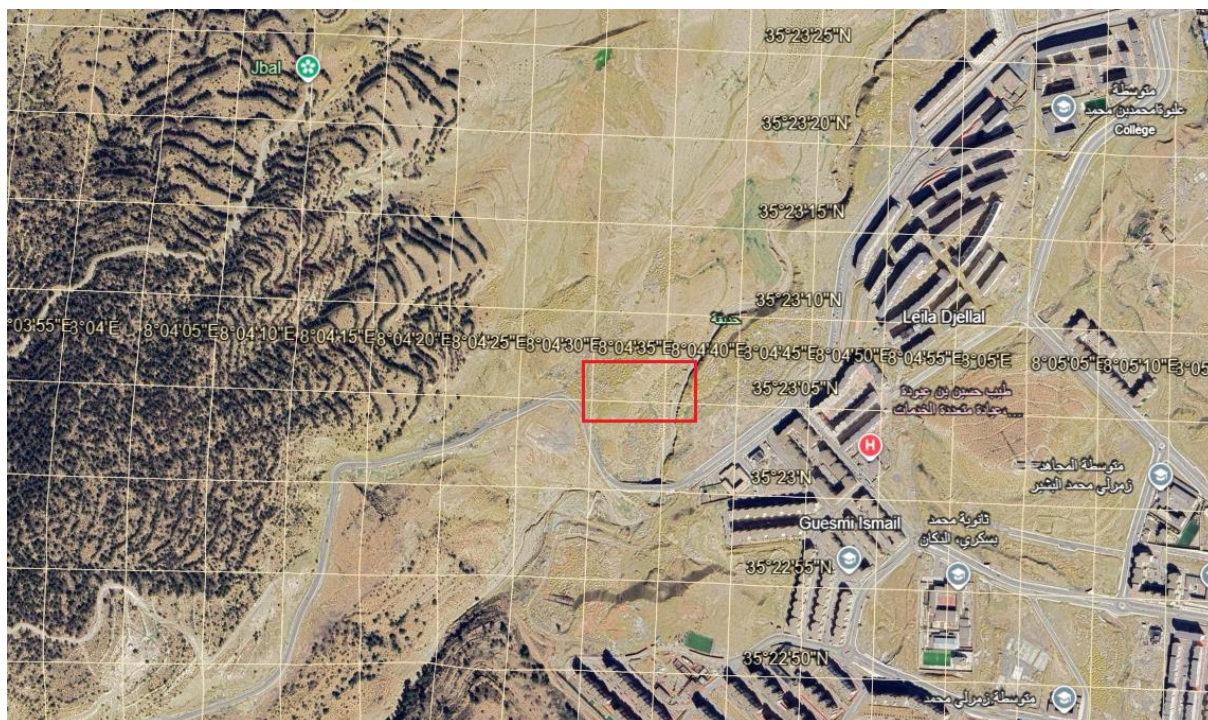


Fig 3.1: Geographic Location of Djebel Dukkan.

3.3 Soil Characterization

This section presents the physical, chemical, and mechanical characterization of the expansive soil collected from Jbel Dukkan. The results provide essential information for evaluating its suitability for improvement using geopolymers.

The tests are listed below in an organized and explained manner:

3.3.1 Physical Tests

Particle Size Distribution

Description: Determines the percentages of sand, silt, and clay in the soil.

Purpose: To identify clay content, which controls the soil's swelling and shrinkage behavior.

Standard: NF P 94-056.



Figure 3.2. Particle size analysis test by wet sieving.

Atterberg Limits

Description:

Liquid Limit (LL): Water content at which the soil behaves like a semi-liquid.

Plastic Limit (PL): Minimum water content where the soil can be molded.

Plasticity Index (PI): Difference between LL and PL.

Purpose: To assess the soil's plasticity and swelling potential.

Standard: NF P 94-051



Figure 3.3. soil's plasticity and swelling test.

Natural Moisture Content

Description: Soil is dried in an oven and the water content is calculated.

Purpose: To determine the soil's natural moisture before treatment.

Standard: NF P 94-050.



Figure 3.4. soil's natural moisture test.

Proctor Compaction Test

Description: Soil is compacted at different moisture contents to determine the maximum dry density.

Purpose: To find Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) for construction purposes.

Standard: NF P 94-093.



Figure 3.5 Proctor Compaction Test

3.3.2 Chemical Tests

Methylene Blue Test

Description: Methylene Blue solution is added to the soil until saturation, indicating active clay content.

Purpose: To determine active clay content.

Standard: NF P 94-068.

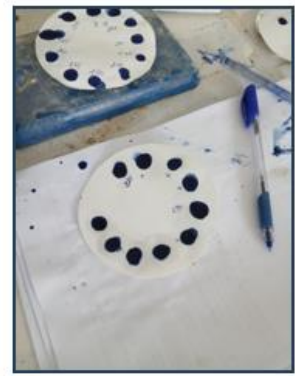


Figure 3.6 Methylene Blue Test

3.3.3 Mechanical Tests

Free Swell Test

Description: Soil is immersed in water and the free expansion is measured.

Purpose: To evaluate the soil's swelling potential.

Standard: NF P 94-071 .



Figure 3.7 Free Swell Test

Oedometer Test

Description: Soil is subjected to incremental loads to measure consolidation, compressibility, and swelling pressure.

Purpose: To determine swelling pressure, compressibility, and consolidation properties.

Standard: NF P 94-093.



Figure 3.8 Oedometer Test

3.4 Results

Table 3.1: tests results.

Test	Result	Unit
LL	61	%
PL	31	%
PI	30	%
Pg	2.2	Bar
VBS	5.73	/
MDD	1.06	g/cm³
OMC	14	%
Dh	1.68	cm

3.5 Discussion

The results obtained from the geotechnical characterization clearly indicate that the studied soil exhibits the typical behavior of a highly expansive clay.

The Atterberg limits show a liquid limit (LL) of 61% and a plastic limit (PL) of 31%, resulting in a plasticity index (PI) of 30%. Such a high PI value reflects a soil with significant plasticity and a strong sensitivity to moisture variations. This behavior is commonly associated with clay minerals capable of absorbing water, leading to considerable volume changes. Therefore, the soil presents a high risk of swelling and shrinkage when subjected to wetting and drying cycles.

The methylene blue value (VBS = 5.73) further confirms the presence of active clay minerals with a high specific surface area. A VBS value of this magnitude indicates a strong affinity between the clay

particles and water, which explains the elevated plasticity and swelling tendency observed in the soil. This result is consistent with the Atterberg limits and reinforces the classification of the soil as expansive.

From a mechanical standpoint, the swelling pressure ($P_g = 2.2$ bar) highlights the potential of the soil to exert significant stresses on foundations and pavements upon wetting. Such swelling pressure is considered high and may cause structural damage if the soil is used in its natural state without treatment. This confirms that the soil is unsuitable for construction purposes unless appropriate stabilization measures are applied.

The Proctor compaction test results indicate a maximum dry density (MDD) of 1.06 g/cm^3 with an optimum moisture content (OMC) of 14%. The relatively low MDD value reflects a loose soil structure dominated by fine particles, which limits its bearing capacity and mechanical performance. This behavior is typical of expansive clay soils and further emphasizes the need for improvement before use in engineering applications.

The dry density ($D_h = 1.68 \text{ g/cm}^3$) obtained under laboratory conditions shows that the soil can be densified; however, this densification alone is insufficient to overcome the problems related to swelling and plasticity. Without chemical or mineral stabilization, the soil remains vulnerable to moisture-induced deformations.

Overall, the combination of high plasticity, elevated VBS value, significant swelling pressure, and low dry density confirms that the soil from Jbel Dukkan is a highly expansive clay. These unfavorable geotechnical properties justify the need for soil improvement. In this context, the use of geopolymer binders based on industrial by-products such as GGBFS and iron mine waste represents a promising solution to reduce swelling behavior, improve mechanical strength, and enhance the durability of the soil.

3.6 Geopolymer Stabilization Methodology

3.6.1 Materials Used

The stabilization of the expansive soil was performed using geopolymer binders derived from industrial by-products, specifically Ground Granulated Blast Furnace Slag (GGBFS) and iron mine waste.

These materials were chosen due to their chemical reactivity, availability, and their potential to improve the mechanical properties of expansive clay soils while contributing to sustainable engineering practices.



Figure 3.9 Materials Used

3.6.2 Preparation of Geopolymer Materials

Before mixing with the soil, both GGBFS and iron mine waste were oven-dried, ground, and sieved to obtain a fine and homogeneous powder. This ensures uniform reaction with the soil particles and effective geopolymerization.

3.6.3 Mixing Proportions

The geopolymer binder was added to the natural soil at different dosages to study the effect of binder content on soil improvement. The adopted proportions were:

5% by dry weight of soil

10% by dry weight of soil

15% by dry weight of soil

This step allows evaluating the influence of geopolymer content on plasticity reduction, swelling control, and mechanical enhancement.



Figure 3.10 percent of geopolymers materials

3.6.4 Mixing and Compaction Procedure

The dry soil was thoroughly mixed with the geopolymer powder to ensure a uniform distribution of the binder. Alcalin solution was then gradually added until the soil reached its Optimum Moisture Content (OMC) determined from the Proctor test.



Figure 3.11 Mixing and Compaction Procedure

3.6.5 Curing Conditions After compaction

The specimens were carefully extracted from the molds, sealed to prevent moisture loss, and cured under controlled laboratory conditions at room temperature. The curing periods were set to 7 and 14 days to allow sufficient geopolymerization reactions between the soil and the industrial binders



Figure 3.12 After compaction

3.6.6 Comparison of Soil Properties Before and After Geopolymer Treatment

A comparison between the natural soil and the soil treated with geopolymer binders highlights significant improvements in its geotechnical behavior. Before treatment, the soil exhibited high plasticity, pronounced swelling potential, and low density, indicating its expansive nature and susceptibility to moisture-induced deformations. The active clay minerals present in the natural soil contributed to these unfavorable characteristics, which pose risks to structural stability.

After stabilization with geopolymer binders based on GGBFS and iron mine waste, the soil properties were markedly improved. The treatment led to a reduction in plasticity and swelling tendency, indicating that the soil became less sensitive to moisture variations. Compaction characteristics were enhanced, resulting in higher dry density and improved mechanical performance, which in turn increases the soil's load-bearing capacity. The results confirm that a moderate geopolymer content is sufficient to mitigate the expansive behavior of the soil effectively.

Overall, the comparison demonstrates that geopolymer stabilization transforms highly expansive clay into a more stable and durable material, suitable for civil engineering applications. This not only validates the efficiency of industrial by-products as sustainable stabilizers but also provides a practical approach to addressing the challenges posed by expansive soils in construction projects.

Table 3.2: Comparison Between before and after Treating the Soils

	Before	After
Plasticity (Atterberg Limits)	High Liquid Limit (LL) High Plasticity Index (PI) Soil classified as highly plastic clay / expansive	Noticeable decrease in LL and PI Soil becomes less plastic and more stable Classification improves to moderately plastic or even low plasticity
Compressive strength	Lower Maximum Dry Density Higher Optimum Moisture Content Difficult compaction due to clay expansion	Increase in Maximum Dry Density Reduction in Optimum Moisture Content Soil becomes easier to compact and more stable
Free Swell Test	Large increase in volume Strong expansion in presence of water	Reduction in free swell percentage Soil expands much less Indicates successful stabilization

3.7 Conclusion

The expansive soil collected from Jbel Dukkan was subjected to a detailed geotechnical characterization, including physical, chemical, and mechanical testing, which confirmed its highly expansive nature. High plasticity, elevated methylene blue value, significant swelling pressure, and low maximum dry density collectively demonstrated the unsuitability of the natural soil for engineering applications without treatment.

The experimental results provided a clear justification for the application of stabilization techniques. The adopted geopolymer treatment methodology, using GGBFS and iron mine waste at varying binder contents, was carefully designed to investigate the influence of geopolymer dosage on soil behavior. The procedures for material preparation, mixing, compaction, and curing were defined to ensure consistency and reproducibility of the laboratory tests, allowing reliable comparison between untreated and treated soils.

The comparison between the natural and geopolymer-treated soil highlighted substantial improvements in geotechnical performance. Reductions in plasticity and swelling potential, improvements in compaction characteristics, and enhanced mechanical behavior demonstrated the effectiveness of geopolymer stabilization in mitigating the adverse effects associated with expansive clays. These findings confirm that geopolymer binders can transform highly expansive soils into more stable and durable materials suitable for civil engineering applications.

In summary, this chapter establishes a robust experimental methodology and provides the necessary baseline data for evaluating the performance of geopolymer-stabilized expansive soils. The procedures and observations presented herein form the foundation for the detailed analysis, discussion, and interpretation of results presented in the subsequent chapter, where the effectiveness of geopolymer stabilization is further quantified and assessed.

GENERAL CONCLUSION

General Conclusion and Prospects

This work has investigated the potential of geopolymers derived from industrial by-products as a sustainable and effective solution for the stabilization of expansive soils. Expansive clays, characterized by high plasticity, significant swelling pressure, and strong sensitivity to moisture variations, present major challenges for geotechnical engineering applications. The adverse effects of these soils on foundations, pavements, and infrastructure highlight the necessity for appropriate treatment techniques that ensure long-term stability and performance.

The first part of the study established a comprehensive theoretical background on expansive soils, emphasizing their mineralogical origins, swelling mechanisms, and associated engineering problems. This review confirmed that traditional stabilization methods, although effective in many cases, suffer from environmental, economic, and durability limitations. The second part of the thesis examined geopolymer technology, highlighting its formation mechanisms, material properties, and advantages over conventional binders. Geopolymers were shown to possess high mechanical strength, low permeability, and excellent chemical resistance, while offering significant environmental benefits through reduced CO₂ emissions and the utilization of industrial waste materials.

The experimental investigation focused on an expansive soil from the Jbel Dukkan region, whose geotechnical characterization confirmed its highly expansive nature. High plasticity index, elevated methylene blue value, significant swelling pressure, and low dry density demonstrated the soil's unsuitability for construction in its natural state. The application of geopolymer stabilization using Ground Granulated Blast Furnace Slag and iron mine waste led to substantial improvements in soil behavior. The treatment resulted in reduced plasticity and swelling potential, improved compaction characteristics, and enhanced mechanical performance, indicating a transformation of the soil into a more stable and durable engineering material.

Overall, the results demonstrate that geopolymer binders are an effective alternative to traditional lime and cement stabilization for expansive soils. Their ability to mitigate swelling behavior while improving strength and durability, combined with their environmental and economic advantages, makes them particularly attractive for sustainable geotechnical engineering applications. This study confirms the feasibility of using industrial by-products for soil stabilization and contributes to the growing body of research supporting geopolymer technology in ground improvement.

Future research may focus on long-term durability under field conditions, optimization of geopolymer mix designs, large-scale implementation, and the performance of geopolymer-stabilized soils under cyclic loading and environmental variations. Nevertheless, the findings of this thesis provide a solid scientific and practical basis for the adoption of geopolymer stabilization as a sustainable solution to the challenges posed by expansive soils.

References

- [1] British Geological Survey (BGS). Shrink–swell soils are those that change volume as a result of changes in moisture content. [Online]. Available: <https://www.bgs.ac.uk>
- [2] Number Analytics – Ultimate Guide to Expansive Soils, which summarizes the mineralogical makeup and behavior of expansive soils.
- [3] Estimation of swelling characteristics of expansive soils with influence of clay mineralogy January 2021 Acta Agriculturae Scandinavica, Section B - Soil & Plant Science 71(3):1-6 DOI: 10.1080/09064710.2021.1872696
- [4] Benramdane, B., Salhi, M., & Seridi, A. (1995).
Caractérisation et comportement des sols gonflants en Algérie.
Revue Française de Géotechnique / études appliquées aux sols algériens.
- [5] Geological Survey Program fact sheet
Missouri Geological Survey Director: Carey Bridges, RG <https://dnr.mo.gov/print/document-search/pub2905>
- [6] H. Komine, N. Ogata, Prediction for swelling characteristics of compacted bentonite, Canadian Geotechnical Journal 33 (1) (1996) pp. 11–22. doi: <https://doi.org/10.1139/t96-021>
- [7] International Journal of Civil Engineering and Technology (IJCIET) – Section: “Problems Associated with Expansive Soils,” includes detailed discussion on structural and geotechnical issues caused by expansive soils.
- [8]
- [9] **Barman & Dash (2022), *Stabilization of expansive soils using chemical additives: A review*** Published in the *Journal of Rock Mechanics and Geotechnical Engineering* — a well-established, peer-reviewed Elsevier journal. This paper thoroughly reviews **lime, cement, and fly ash stabilization** mechanisms (hydration, cation exchange, flocculation, pozzolanic reactions), effects on expansive soils, and factors influencing performance.
- [10] Fredlund, D. G., & Rahardjo, H. (2000). Expansive Soils – Encyclopedia of Engineering Geology. Link
- [10] A Case History of Structures Constructed on Expansive Soils John D. Nelson et al., (2015).

[11] Compressive Strength of Sandy Soils Stabilized with Alkali-Activated Volcanic Ash and Slag
November 2021 Journal of Materials in Civil Engineering

[12] Davidovits, J. (2015). Geopolymer Chemistry and Applications (4th Edition). Institut Géopolymère, France.

[13] Geopolymer concrete in construction projects: a review (Springer) – detailed analysis of compressive strength, microstructure and durability.

[14] Physical, Mechanical and Durability Properties of Eco-Friendly Engineered Geopolymer Composites (MDPI) – overview of engineered composites and physico-mechanical properties.

[15] Unveiling physico-mechanical characteristics of fly ash geopolymers through density and porosity (Journal of Building Engineering) – insight into density–porosity effects.

[16] Durability of geopolymers and geopolymer concretes: A review (Reviews on Advanced Materials Science) – chemical resistance, permeability, and freeze–thaw behaviour.

[17] Study on Stress-Strain effect of reinforced Metakaolin based GPC under compression
November 2019 Materials Today Proceedings

[18] Broader insights into expansive soil mineralogy and swelling mechanisms and stabilization strategies: Improvement of Expansive Soils: A Review Focused on Applying Chemical and Sustainable Methods.

[19] Scientific evidence that geopolymer stabilization reduces swelling in expansive soils, improves strength, and modifies microstructure:

Geopolymer-stabilized expansive soils using zeolitic tuff and industrial by-products — observed significant reductions in swelling behavior and improved geotechnical performance.

[20] Demonstration of enhanced mechanical behavior and plasticity modification from fly ash-based geopolymer stabilization

[21] Detailed evaluation of durability and performance metrics for geopolymer-treated expansive soils: Durability Of Geopolymer Stabilization Of Expansive Soils – A Review.

[22] Abdullah, H. H., Shahin, M. A., & Walske, M. L. (2020). Review of Fly-Ash-Based Geopolymers for Soil Stabilisation with Special Reference to Clay. Geosciences, 10(7), 249.