



Nazarbayev University

THE COMBINED EFFECT OF PARTICLE SIZE AND STABILIZER OF BOFS ON SULFATE-BEARING KAOLIN CLAY

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OUTLINE

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- **Research Objectives**
- **Experimental Program**
- **Results**
- **Discussion**
- **Conclusion**
- **Future work**

Introduction

Sulfate - bearing soils

Sulfate-bearing soils are soils that contain significant concentrations of sulfate salts, primarily in the form of minerals such as:

- Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$)
- Anhydrite (CaSO_4)
- High levels of **Sulfate Ions** (SO_4^{2-}) specifically

Saline Soils cover more than 41% of the total area of Kazakhstan

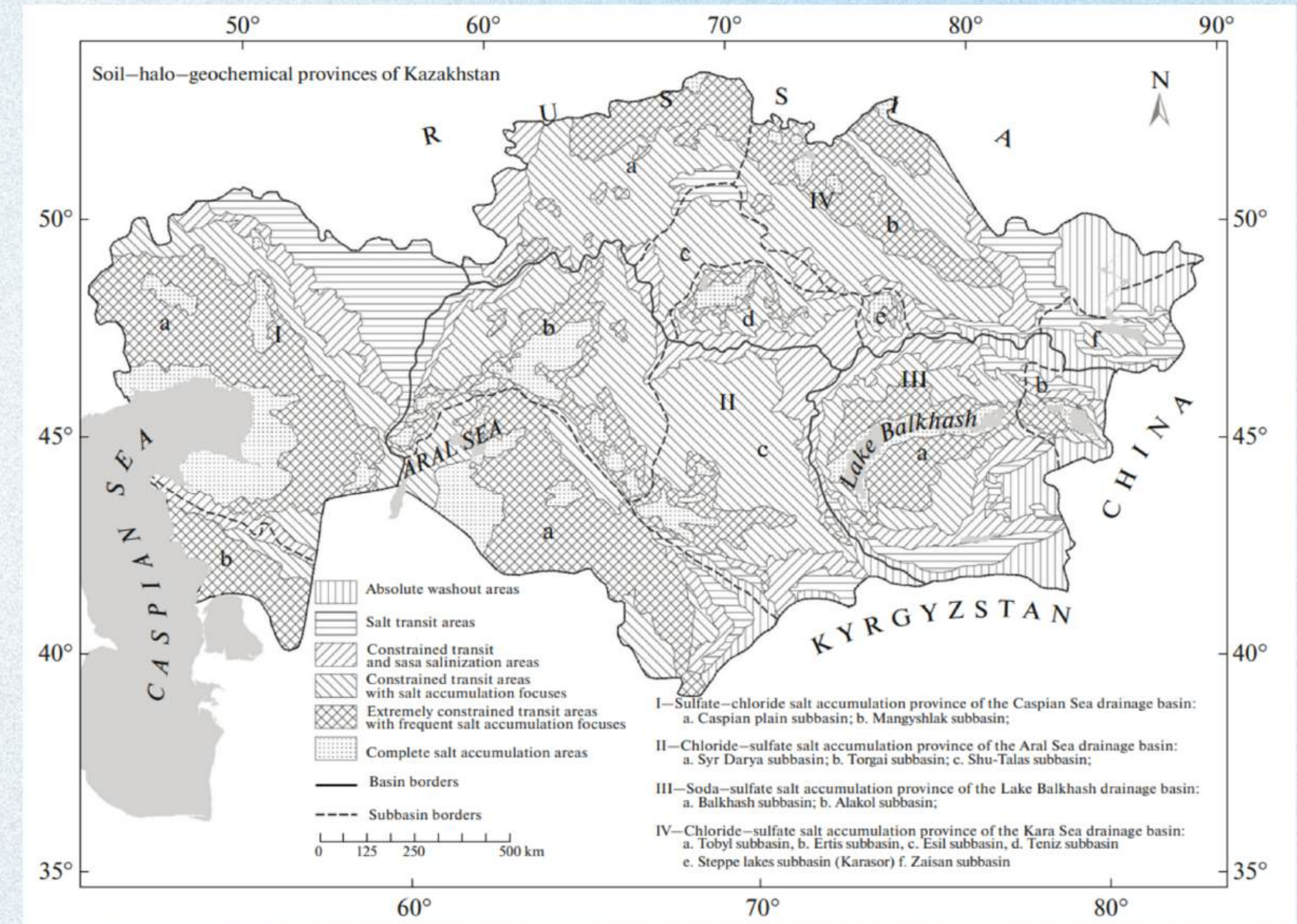


Fig 1. Soil-halo-geochemical provinces of Kazakhstan [1]

Ettringite Formation

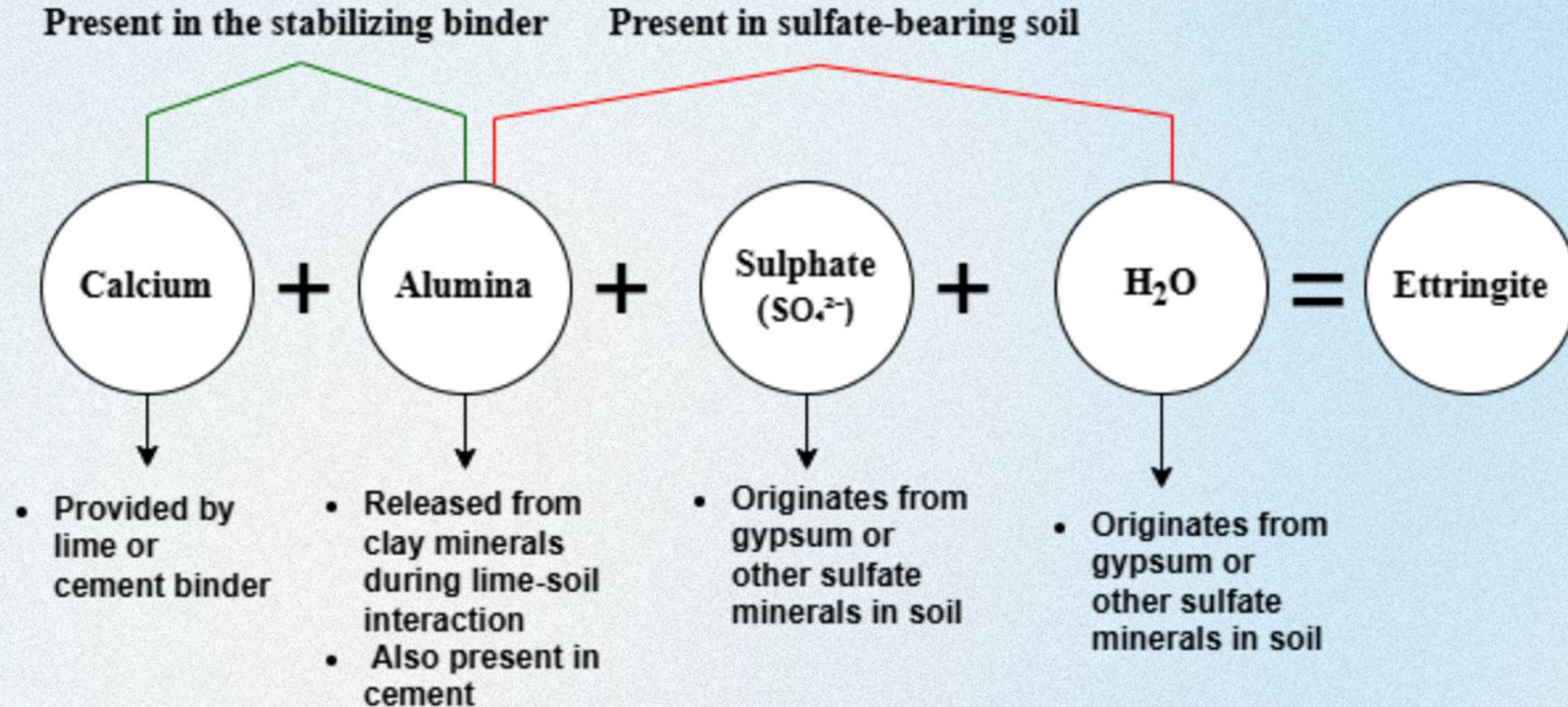


Fig 2. Ettringite formation mechanism in sulfate-bearing soil treated with cement and lime

Sulfate - induced heave

Ettringite is an expansive mineral that can **expand significantly** and cause:

- Heaving (uplift of stabilized layers)
- Cracking and failure of pavements or foundations
- Especially dangerous in high-sulfate soils treated with lime or cement

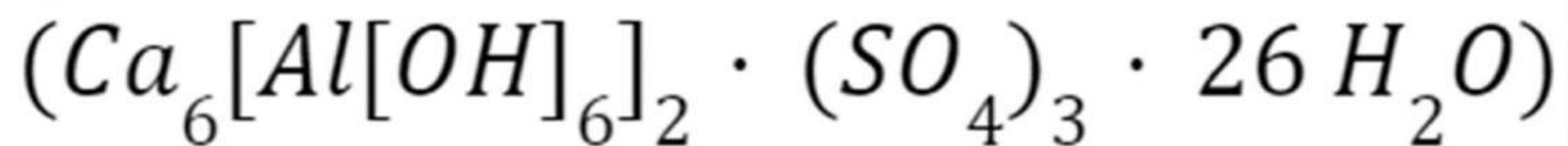


Fig 3. Sulfate induced heaving of a pavement in India [2]

Sulfate level	Calcium-based stabilization
<3000 ppm	Low risk
3000–5000 ppm	Modest risk
5000–8000ppm	Modest to high risk
>8000 ppm	Serious risk
<1000 ppm	Low risk
1000–2500 ppm	Ok at elevated lime concentratio
>2500 ppm	High risk
<3000 ppm	No risk
3000–7000 ppm	Ok with mellowing
>7000 ppm	High risk

Fig 4. Levels of risk sulfate bearing soil stabilized with cement [3]

Literature Review

Soil Stabilization

- **Soil Stabilization** is the process of improving the physical and mechanical properties of soil to make it suitable for construction purposes
- **Goals:**
 - Increase strength
 - Reduce swell
 - Improve durability
- **Methods of Soil Stabilization:**
 - Mechanical stabilization
 - Chemical stabilization
 - Cement stabilization
 - Lime stabilization
- **Use of Alternative Stabilizers:**
 - Industrial by-products
 - BOFS
 - GGBFS

Why BOFS in Soil Stabilization?

- **Sulfate Compatibility:**
 - Unlike lime and cement, BOFS has **lower calcium content**
 - Reduces the risk of **ettringite formation**, making it ideal for sulfate-rich soils
- **High Alkalinity:**
 - Supports **pozzolanic reactions** without generating excess calcium hydroxide
- **Mechanical Improvement:**
 - Increases compressive strength, durability, and resistance to environmental stress

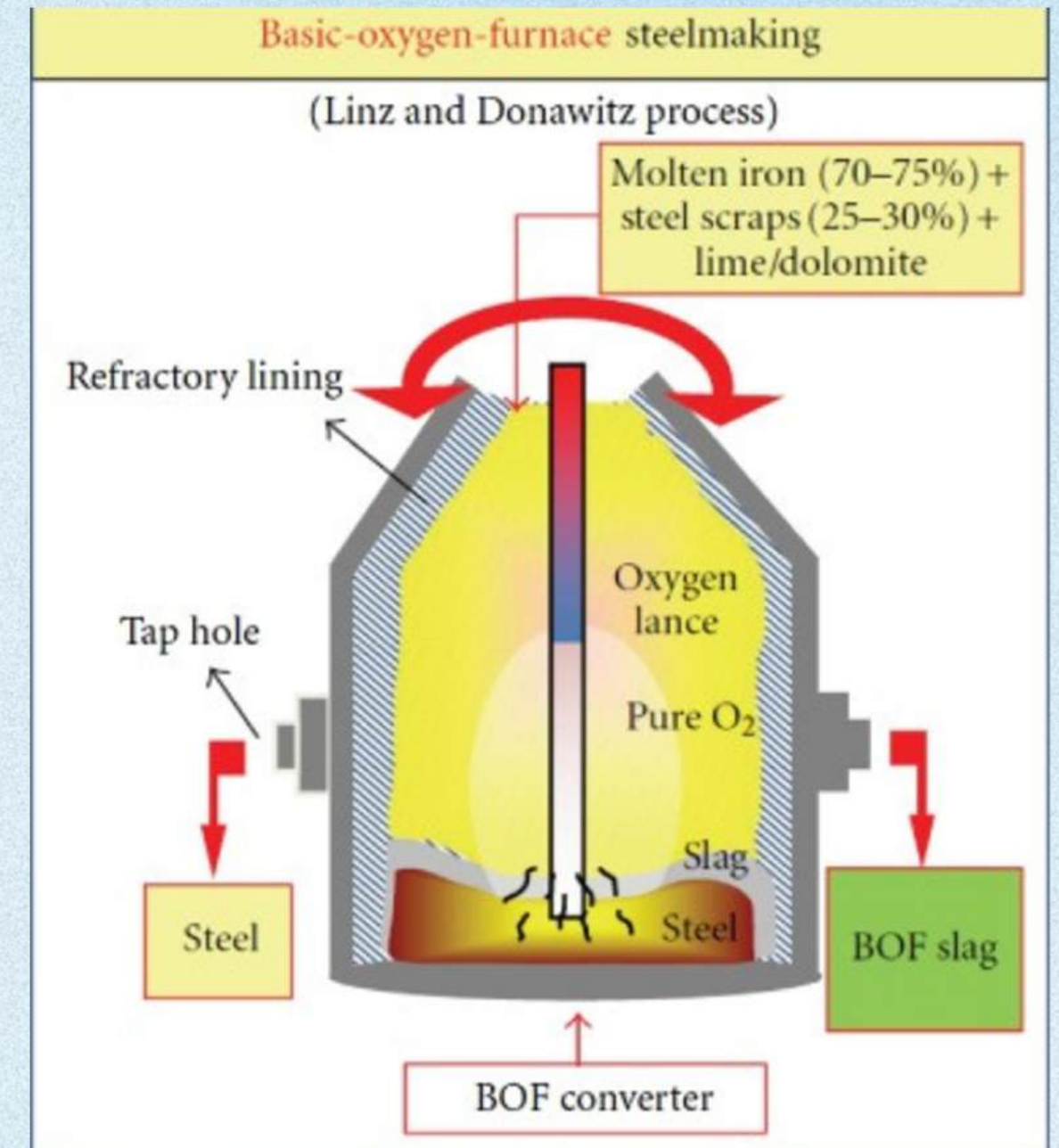


Fig 5. Basic Oxygen Furnace Steelmaking Process [4]

Utilization of BOFS in KZ

- Promotes **sustainable use** of industrial waste.
- Aligns with Kazakhstan **2050 Green Growth Strategy**.
- Reduces land use and management costs of steel slag disposal.
- Proposed Local Applications:
 - Asphalt concrete, railway ballast, winter abrasives, snow barriers, fertilizer, artificial hills, and soil neutralization.



Fig 5. Basic Oxygen Furnace Slag (BOFS) stockpile at JSC "ArcelorMittal Temirtau" site, Kazakhstan.

BOFS as a Soil Stabilizer

- Li et al. (2018):
 - Investigated the incorporation of BOFS into clay soils and observed significant **improvements in unconfined compressive strength** (UCS), durability, and **reduced permeability**.
- Elbaz et al. (2020):
 - Explored the application of BOFS in stabilizing soils subjected to freeze-thaw cycles. The study found that BOFS significantly **enhanced the freeze-thaw resistance** of the stabilized soils, making it suitable for use in cold climates.
- Zhou et al. (2021):
 - Examined the use of BOFS as an alternative to lime for stabilizing sulfate-rich soils. The research demonstrated that BOFS effectively **minimized sulfate-induced expansion** by buffering against the formation of expansive minerals like ettringite.

Importance of Particle Size in Soil Stabilization

- Rao et al. (2016):
 - Showed that **finer fly ash** particles in a fly-lime mix reduced swelling and enhanced long-term strength.
- Shi et al. (2000):
 - Found that **finer GGBFS** particles led to higher early strength due to faster hydration, but may compromise long-term durability.
- Kim et al. (2023):
 - Smaller **bottom ash** particles enhanced the strength of composite geomaterials with curing time.
- He et al. (2022)
 - Used the Rosin-Rammler-Bennett model to evaluate PSD of **GGBFS** and linked finer sizes to increased mortar strength and workability.

Hypothesis

1.

BOFS is hypothesized to exhibit a dual functionality:

- Chemical Function
- Physical Function

2.

Particle size effect of BOFS:

- Certain BOFS particle fractions improves bonding and pozzolanic activity

3.

Strength development of stabilized sulfate-bearing kaolin clay is possible based on the particle size of BOFS

Objectives

1.

Effectiveness of BOFS:

- To access how BOFS performs as a stabilizer for kaolin clay with high sulfate content

3.

Durability:

- To access how BOFS performs as a stabilizer for kaolin clay with high sulfate content

2.

BOFS Particle Size:

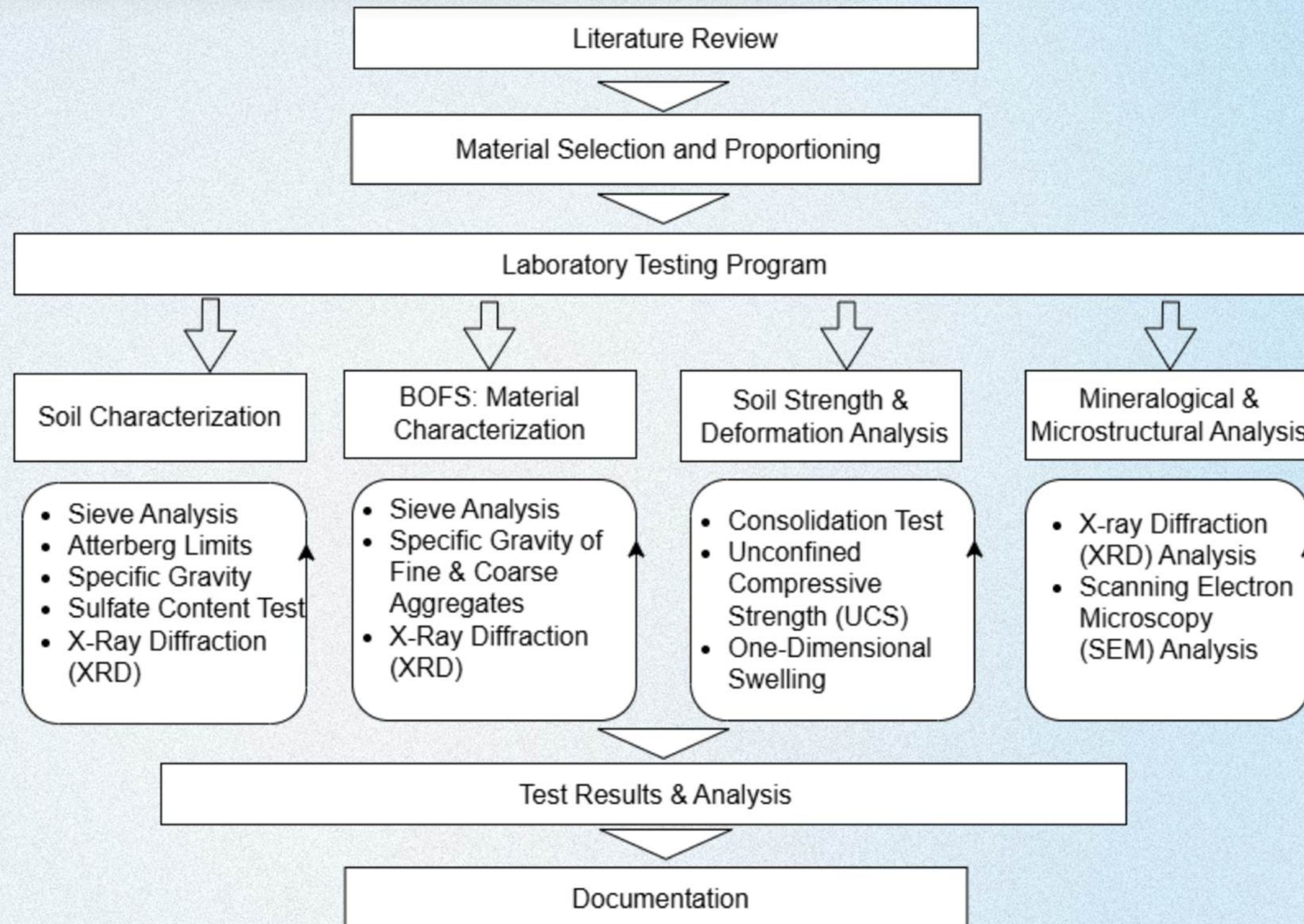
- To explore the relationship between different BOFS particle sizes and the mechanical properties of the stabilized kaolin clay

4.

Strength Prediction:

- Develop a reliable predictive model that estimates the unconfined compressive strength (UCS) of high-sulfate-bearing kaolin clay treated with BOFS

Experimental Program



Material & Geotechnical Characterization

Characterization of Basic Oxygen Furnace Slag

Sieve Analysis

- Conducted per ASTM C136 using 67 kg of BOFS
- Balanced mix of coarse and fine particles
- Used in strength prediction calculations

Specific Gravity

- AASHTO T 84 (fine aggregates) and T 85 (coarse aggregates)
- Values: 2.98 & 3.22, average: 3.1
- Dry density: 5.30 g/cm³

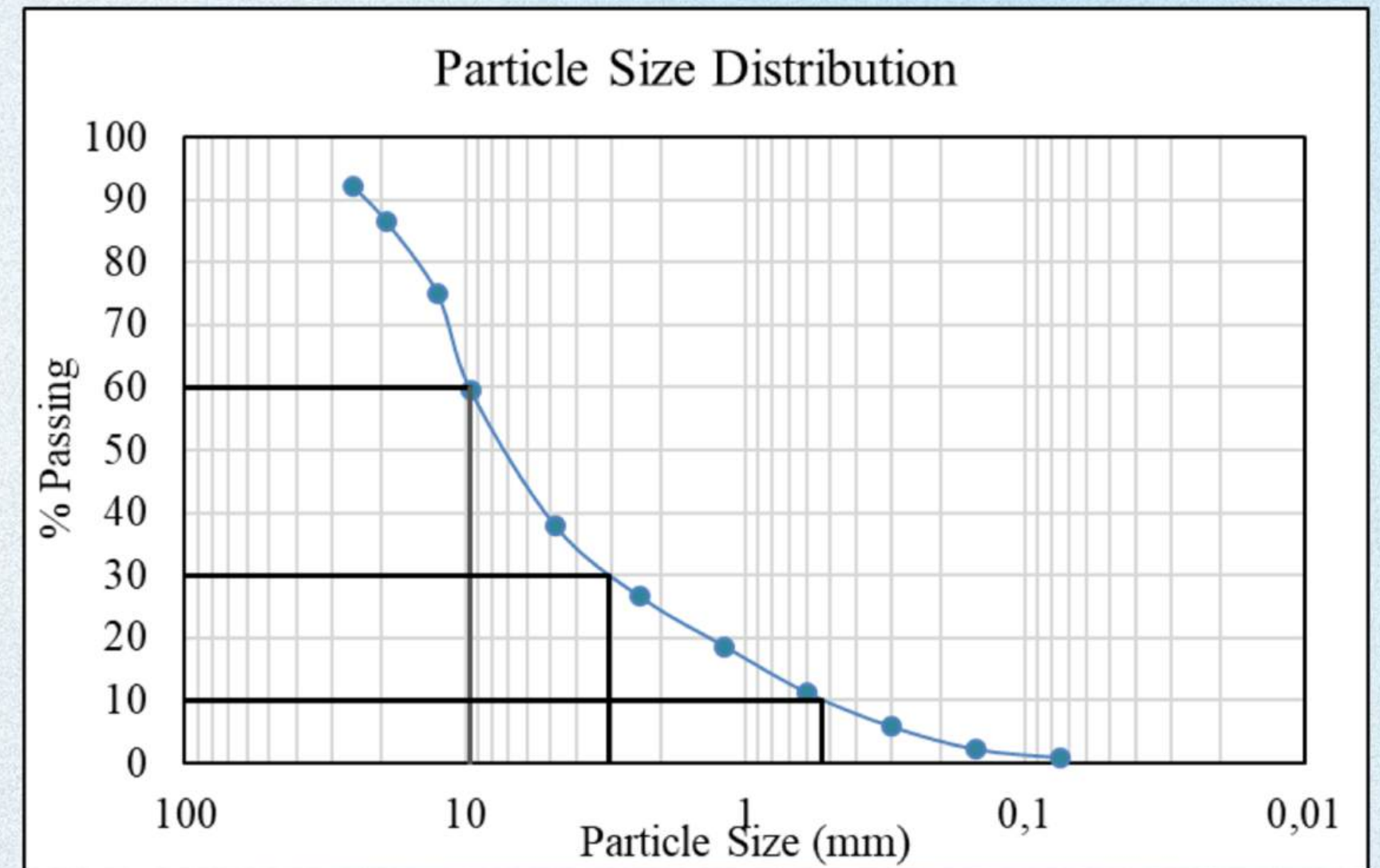


Fig 6. Particle Size Distribution of BOFS

Characterization of Basic Oxygen Furnace Slag

XRD Analysis

- Identified crystalline phases:
 - Lime (CaO), Hematite (Fe₂O₃), Quartz (SiO₂)

XRF Analysis

- Main oxides:
 - CaO (52.38%), Fe₂O₃ (29.39%), SiO₂ (7.39%)

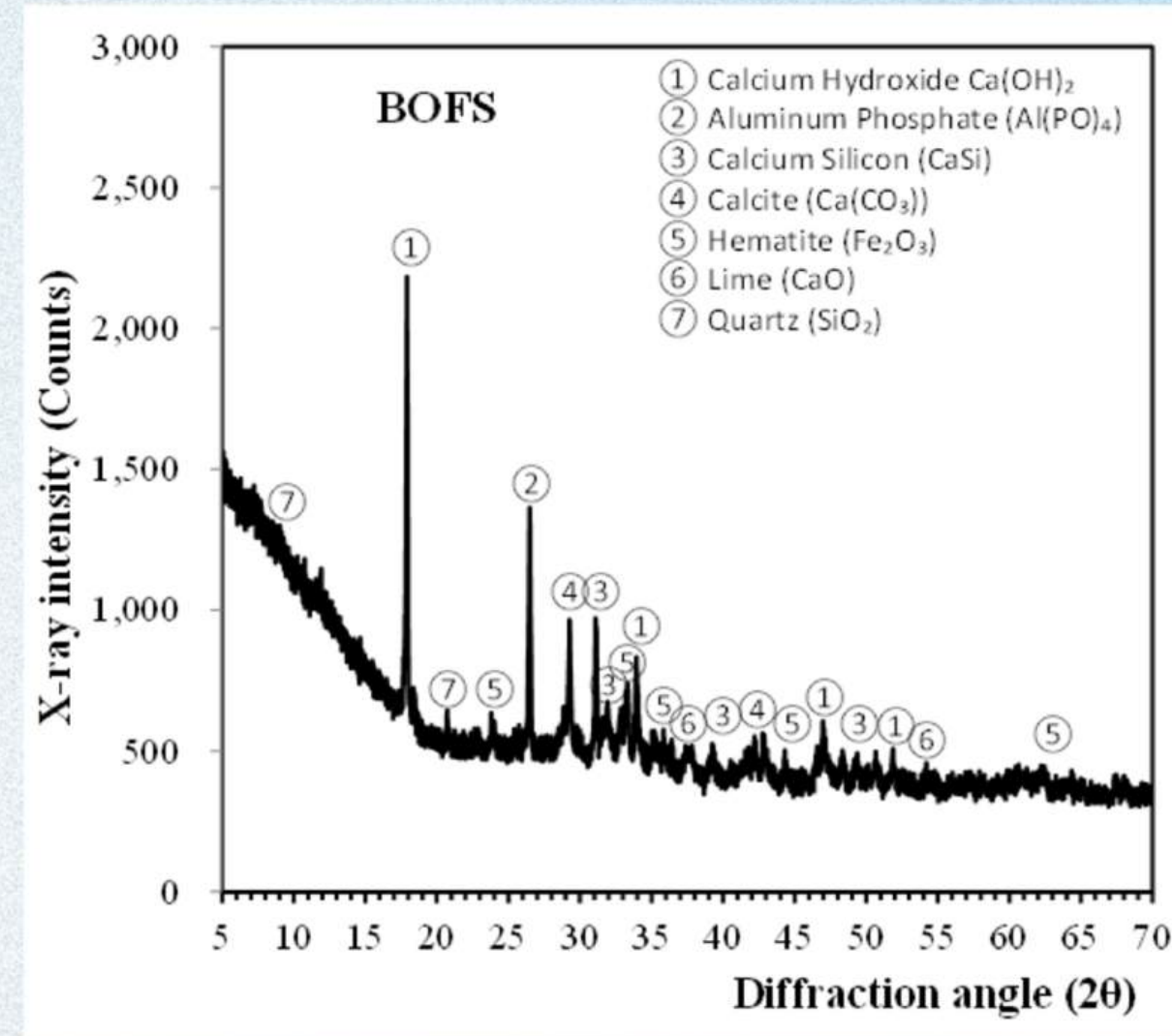


Fig 7. Crystalline phases of BOFS materials.

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	K ₂ O	MnO	P ₂ O ₅	MgO	SO ₃
BOFS	7.39	1.53	29.39	52.38	-	4.33	-	3.13	0.23

Fig 8. Chemical composition of BOFS materials

Soil Classification

Artificial Soil

- 80% - Kaolinite
- 20% - Gypsum

Sieve Analysis (ASTM D6913)

- Most particles retained in #140 & #200 fine-grained clay

Atterberg Limits (ASTM D4318)

- Liquid Limit (LL): 56.51%
- Plastic Limit (PL): 34.83%
- Plasticity Index (PI): 21.68% High-plasticity clay

Soil Classification

- USCS: CH Clay of High Plasticity
- AASHTO: A-7-5 Fine-grained clay with high plasticity

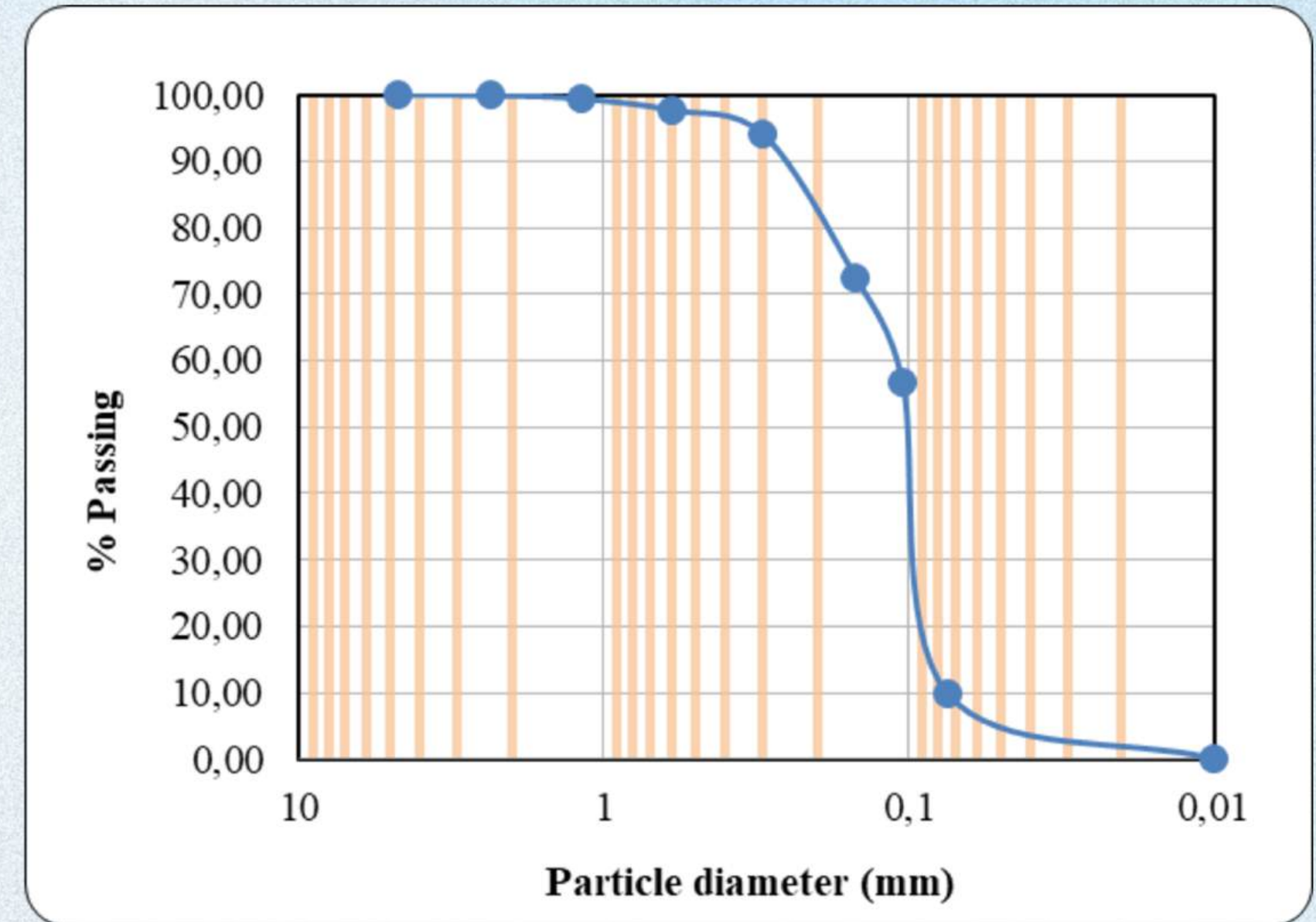


Fig 9. Particle Size Distribution of Kaolin Clay

Mineralogy & Specific Gravity

🧪 Specific Gravity (ASTM D854)

- Trials: 2.39, 2.51, 2.69 Avg:
2.54 g/cm³

🧪 XRD Analysis

- Crystalline Phases: Kaolinite, Quartz, Gypsum
- Kaolinite treated with gypsum

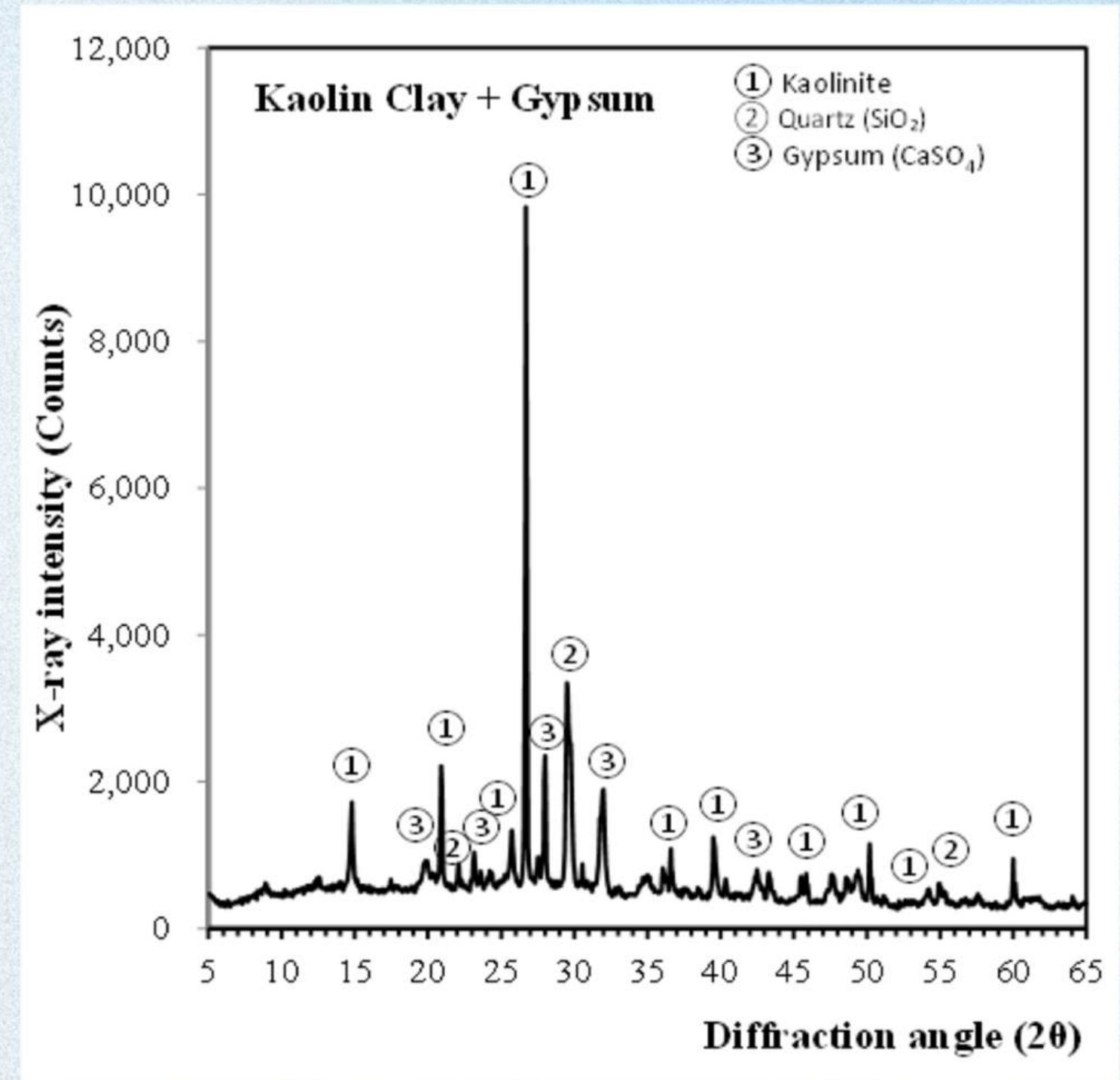


Fig 10. XRD analysis of kaolin clay treated with gypsum.

Effective BOFS Addition Rate Determination

Effective BOFS Addition Rate Determination

Consolidation Test

- Objective: The determination of the Optimal BOFS Addition Rate by evaluating the settlement and compressibility of stabilized soil
- Modified ASTM D2435 (One-Dimensional Consolidation Test)
- Novelty: Applied to BOFS-stabilized soils

Table 1. Pre- Mix Design for Consolidation Testing

Mixture	BOFS Addition Rate (RBOFS(volumetric), %)	BOFS Particle Size	Water Content
1	20	All sizes combined(#4-#200)	1.5 x LL
2	30		
3	40		

$$R_{BOF} = \frac{V_{BOF}}{V_{soil} + V_{water} + V_{BOF}} \times 100 \quad (\%)$$

Fig 11. Crystalline phases of BOFS materials.

Effective BOFS Addition Rate Determination

⚙️ Test Setup

- Samples: $\text{Ø}50 \text{ mm} \times \text{H}20 \text{ mm}$ (trimmed from 100 mm mold)
- Equipment: ELE International Oedometer
- Loading: 5, 10, 20, 40, 80 kg (incremental)
- Final unloading to 0 kg to analyze rebound behavior
- Real-time settlement tracking via DS 7.2 software



Fig 12. Chemical composition of BOFS materials



Fig 13. Consolidation Test Apparatus

Effective BOFS Addition Rate Determination

Results

- 20% & 30% BOFS gave optimal compressibility reduction
- 40% BOFS had lowest settlement but reduced workability

Table 2. Coefficient of volume compressibility (mv), compression index (Cc), and coefficient of consolidation (Cv) for different BOFS addition rates.

RBOFS (volumetric)	mV (m ² /kN*10 ⁵)	Compression Index (Cc)	Coefficient of Consolidation, Cv (m ² /year)
20%	9.00	0.06	0.85
30%	15.77	0.07	1.05
40%	6.00	0.04	0.92

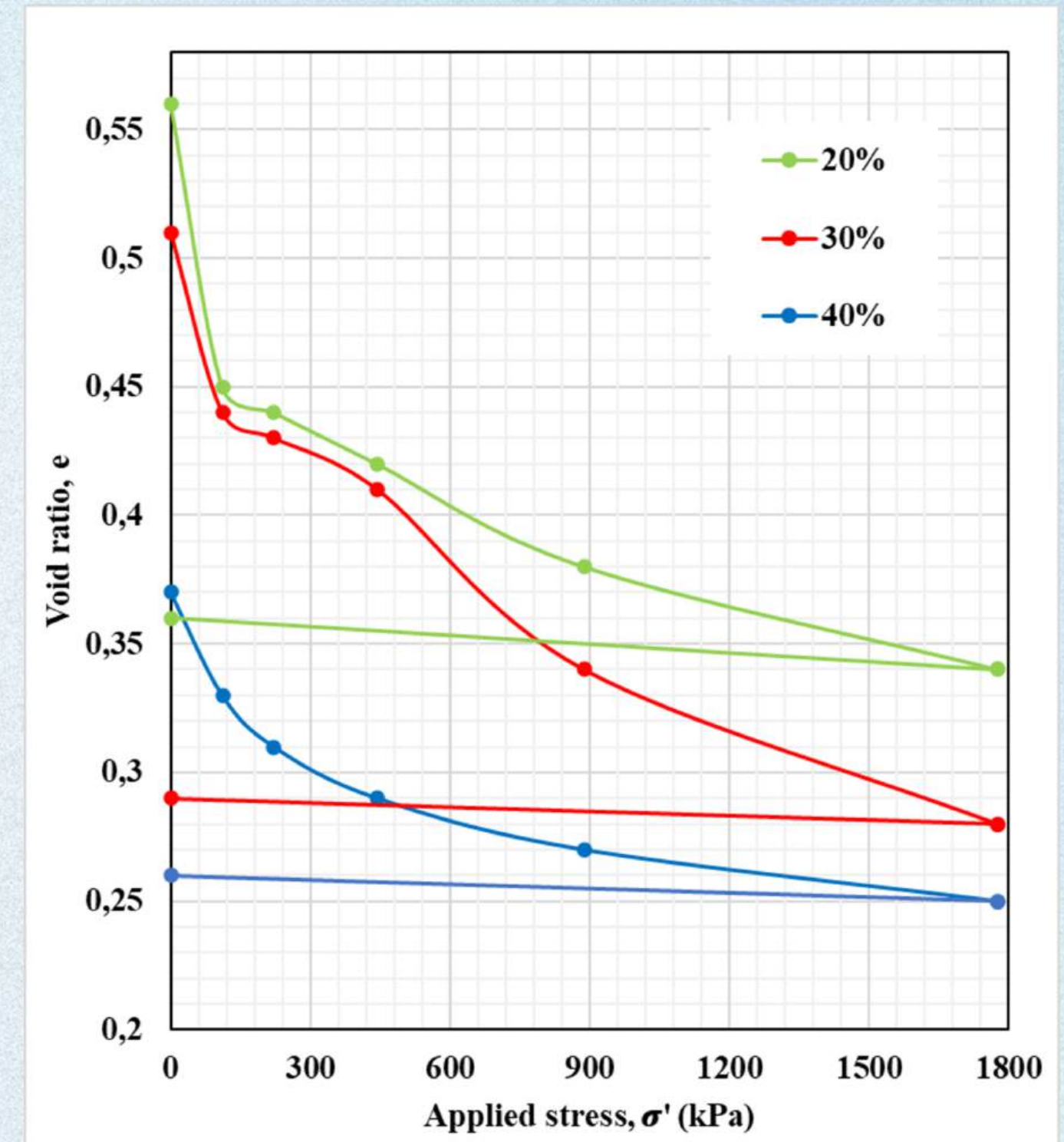


Fig 14. Void ratio to applied stress for different volumetric BOFS addition rates.

Optimal BOFS Particle Size Classification

Optimal BOFS Particle Size Classification

Unconfined Compressive Strength (UCS) Test (ASTM D2166)

- Purpose: To determine which BOFS particle size range most effectively improves UCS of high-sulfate bearing kaolin clay
- Specimen: 50 mm in diameter and 100 mm in height

Table 3. Pre-mix design for optimal particle size classification (pre-UCS test).

Mix	BOFS Particle Size	RBOFS (volumetric), %
1	25mm - #4(25mm, 19mm, 9.5mm, & 4.75 mm)	30
2	#4 - #20(4.75 mm, 2.00mm, & 0.85mm)	
3	#4 - #40(4.75 mm, 2.00mm, 0.85mm, & 0.425mm)	
4	#4 - #60(4.75 mm, 2.00mm, 0.85mm, 0.425mm, & 0.25 mm)	
5	#4 - #100(4.75 mm, 2.00mm, 0.85mm, 0.425mm, 0.25mm & 0.15mm)	



Fig 15. Triaxial test machine

Optimal BOFS Particle Size Classification

Results:

- **Time-Dependent Strength Gain**
 - Due to ongoing hydration and pozzolanic reactions
- **Finer BOFS particles = Higher UCS**
 - Increased pozzolanic reactivity
 - Better void filling
 - Enhanced bonding particles
- **Coarser BOFS particles = Lower UCS**
 - The 25 mm – #4 fraction performed the worst
 - Coarse particles contributed more to mechanical reinforcement than chemical stabilization.

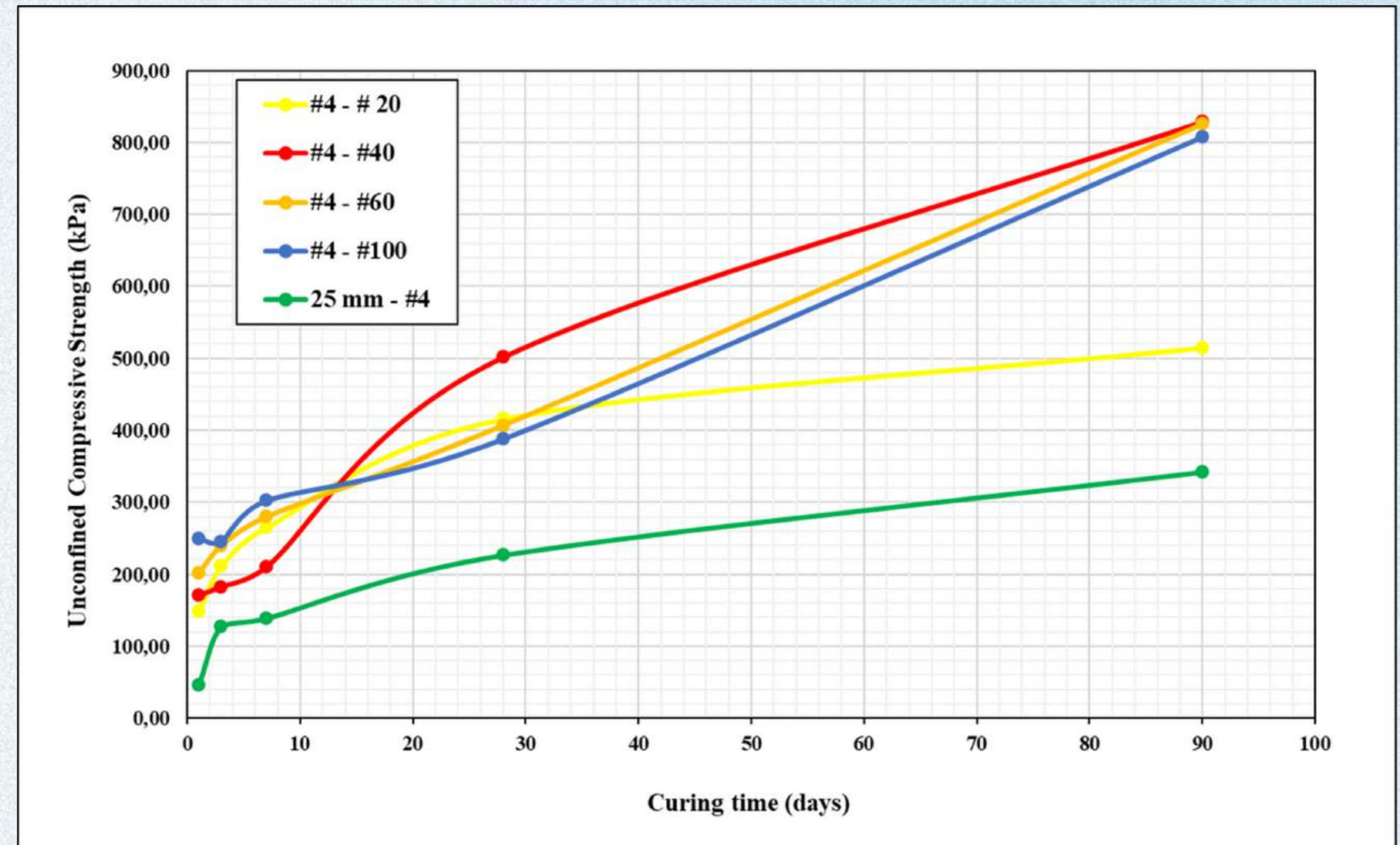


Figure 16. UCS curves for optimal BOFS size determination.

Strength Characteristics

Strength Characteristics

Unconfined Compressive Strength (UCS) Test (ASTM D2166)

- Purpose: To determine which BOFS particle size range most effectively improves UCS of high-sulfate bearing kaolin clay
- Specimen: 50 mm in diameter and 100 mm in height

Table 4. Mix design for soil strength analysis

Mixture	BOFS Particle Size	BOFS Addition Rate	
		RBOFS (volumetric), %	RBOFS (mass), %
1	#100 - #4(0.15mm, 0.25mm, 0.425mm, 0.85mm, 2.00mm, & 4.75mm)	20 & 30	20 & 30
2	#100 - #10(0.15mm, 0.25mm, 0.425mm, 0.85mm, & 2.00mm)		
3	#100 - #20(0.15mm, 0.25mm, 0.425mm, & 0.85mm)		
4	#100 - #40(0.15mm, 0.25mm, & 0.425mm)		

Volumetric BOFS Addition – UCS Trends

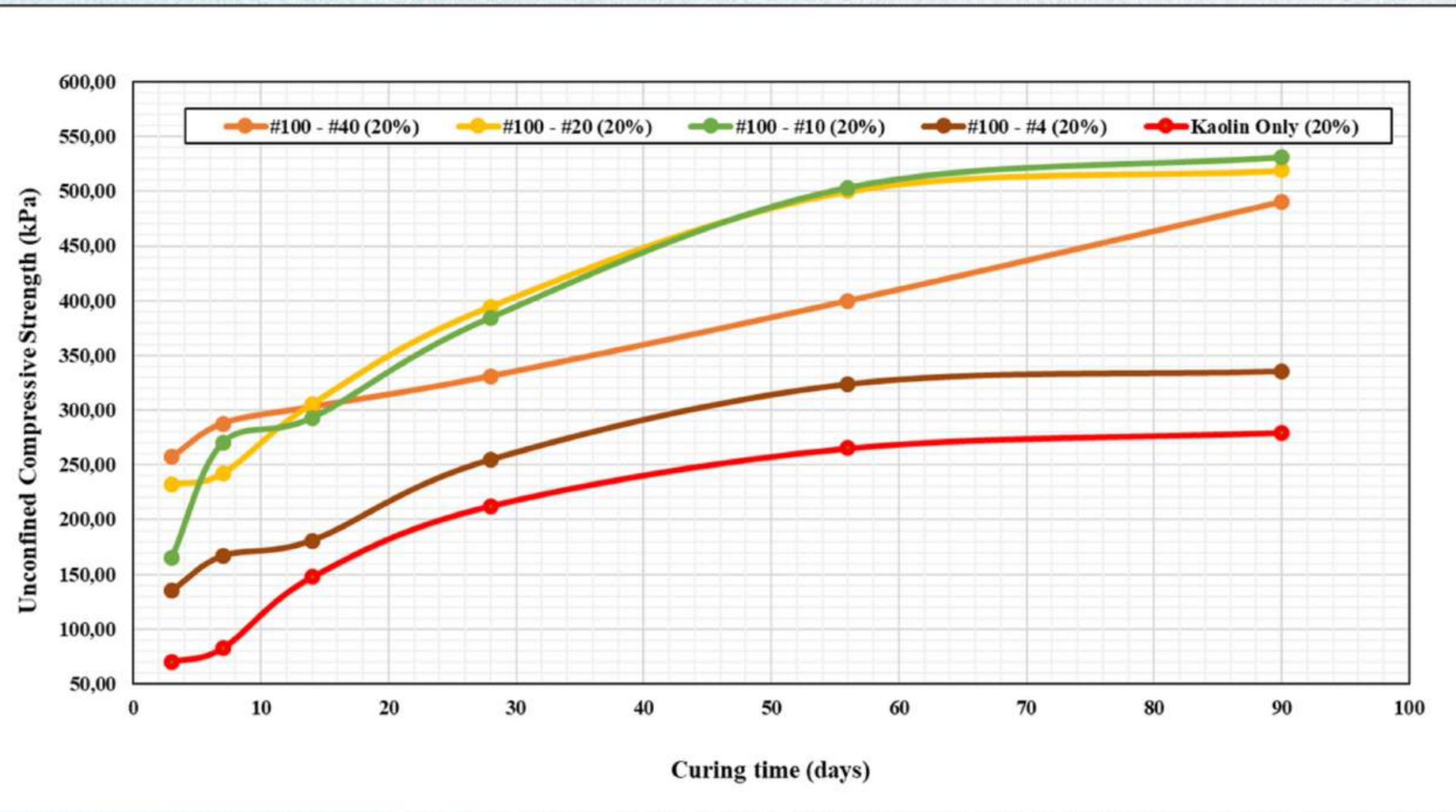


Fig 17. UCS curves for RBOFS (volume)= 20%

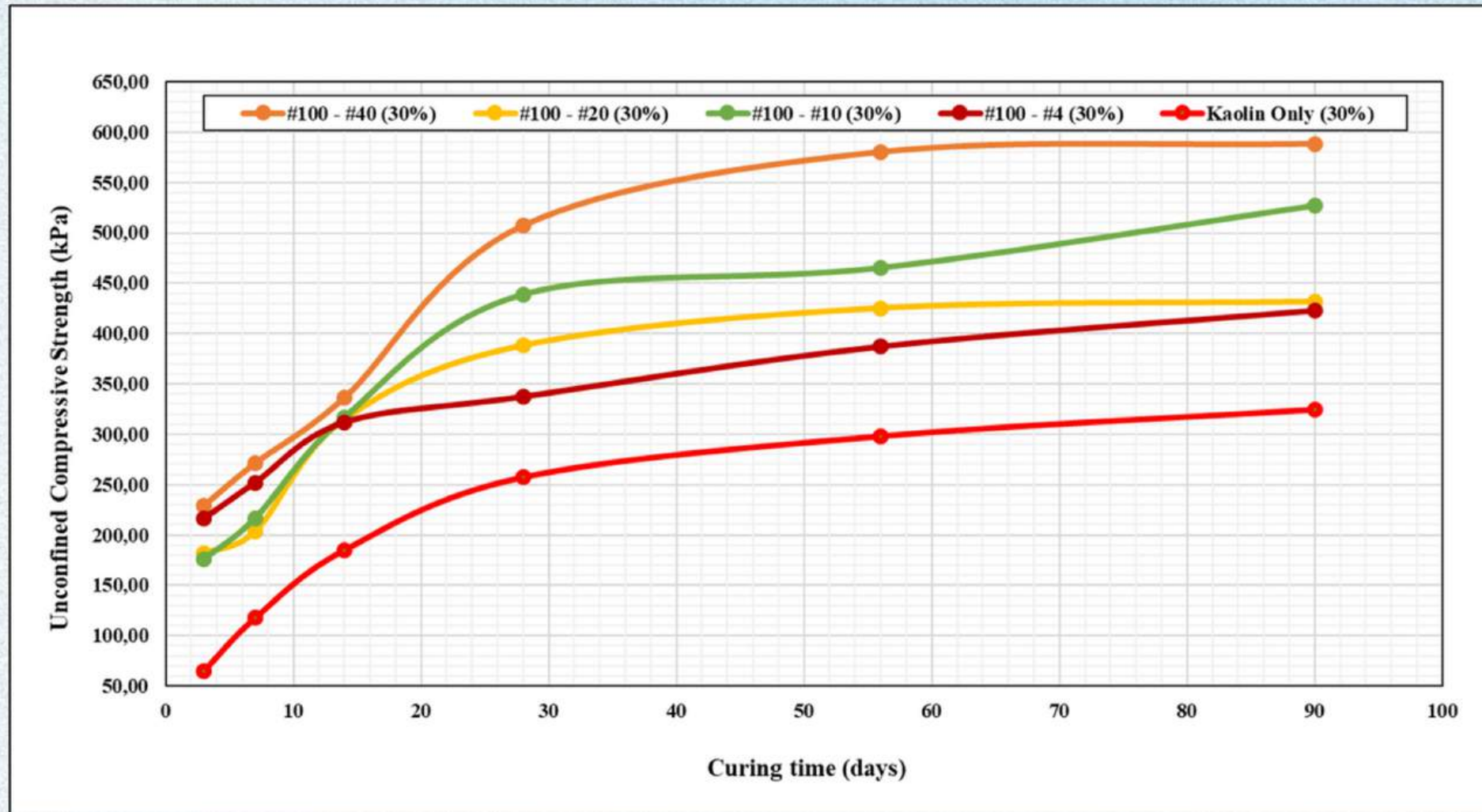


Fig 18. UCS curves for RBOFS(volume)= 30%

Key Findings:

- **Finer** BOFS particles (#100–#40, #100–#20) **Higher UCS**
- **Best** UCS (531.11 kPa at 90 days) with #100–#10 at 20%
- At 30%, moderate-fine particles (#100–#40) performed best 600 kPa

Mass BOFS Addition – UCS Trends

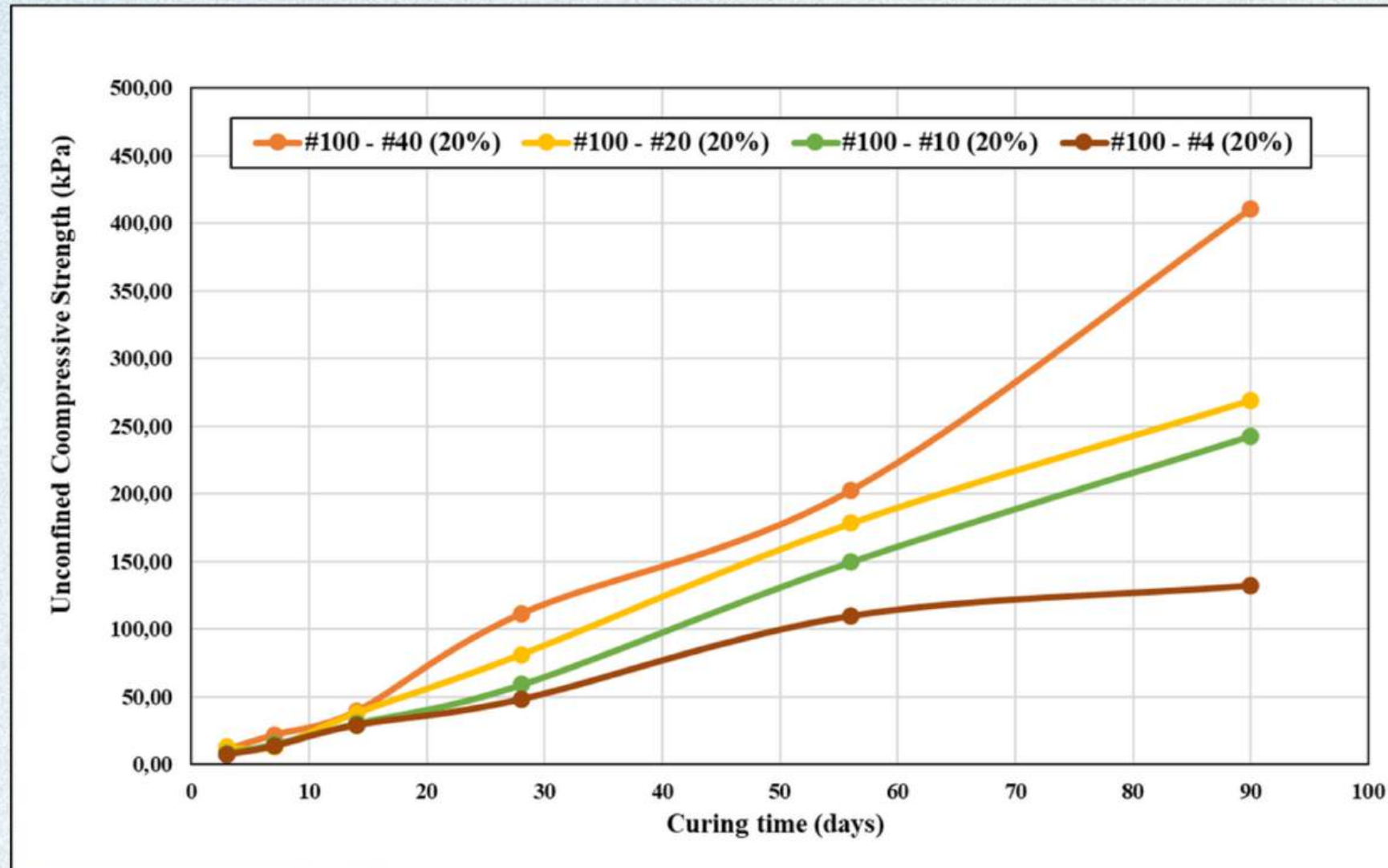


Fig 19. UCS curves for RBOFS (mass)= 20%

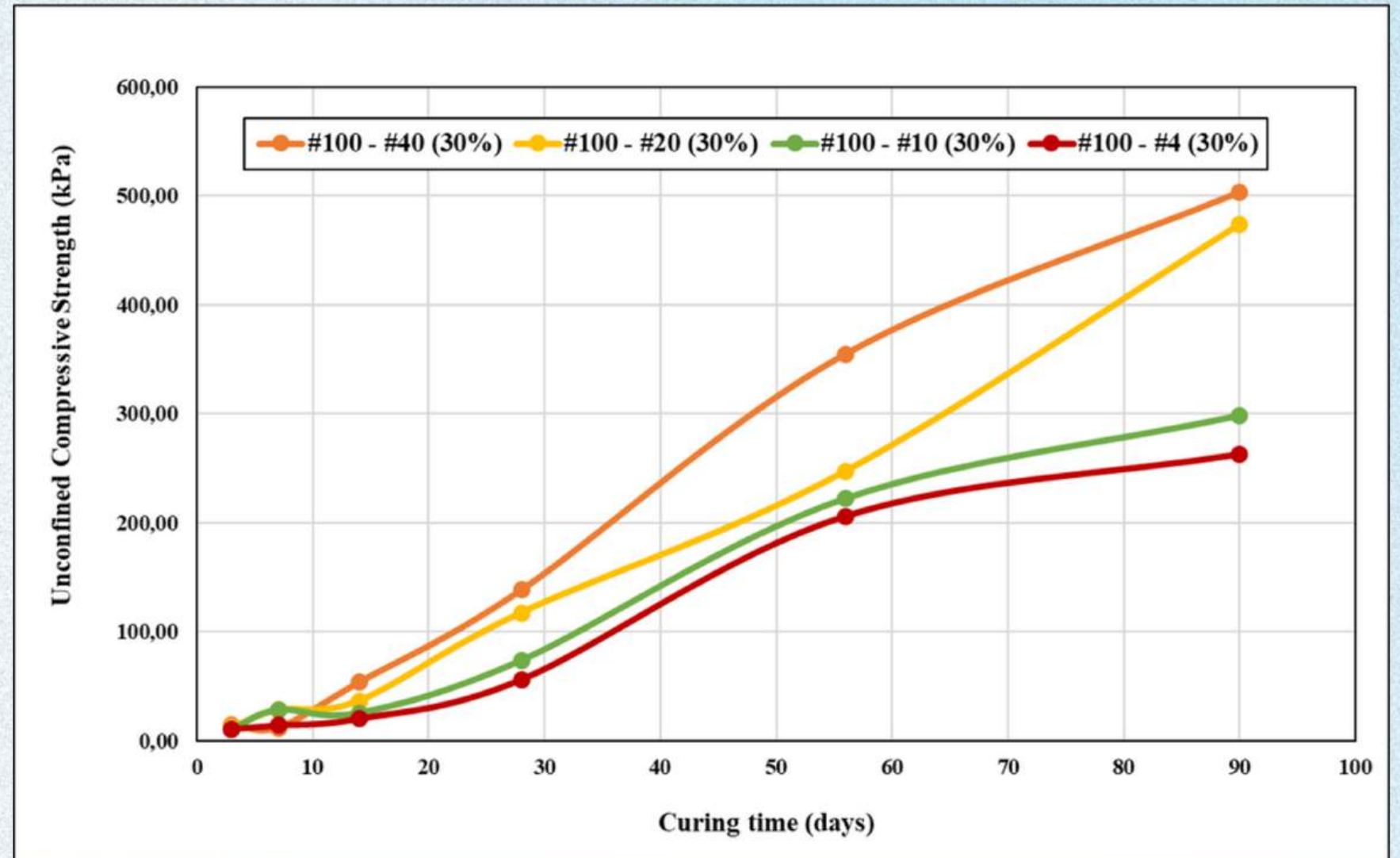


Fig 20. UCS curves for RBOFS (mass)= 30%

Key Findings:

- **Finer** particles again show **higher UCS**
- At 30% mass: #100–#60 639.42 kPa
- At 20% mass: #100–#40 410.92 kPa
- **Coarser blends** (#100–#4) yielded the **lowest UCS values**

Summary – Factors Affecting Strength

Factor	Effect on UCS
Particle Size	Finer particles = Higher strength (faster pozzolanic reaction)
BOFS Addition Rate	30% > 20% (more binder more strength)
Curing Time	Strength with time (hydration pozzolanic bonding)

Swelling Behaviours

Swelling Behaviour

One-Dimensional Swelling Test

- Objectives:
 - To evaluate the one-dimensional swelling behavior of high-sulfate-bearing kaolin clay stabilized with BOFS;
 - To assess how different BOFS particle sizes influence the expansion and volume changes of the stabilized soil under sulfate-rich conditions
- Vertical and volumetric expansion were measured for 14 days

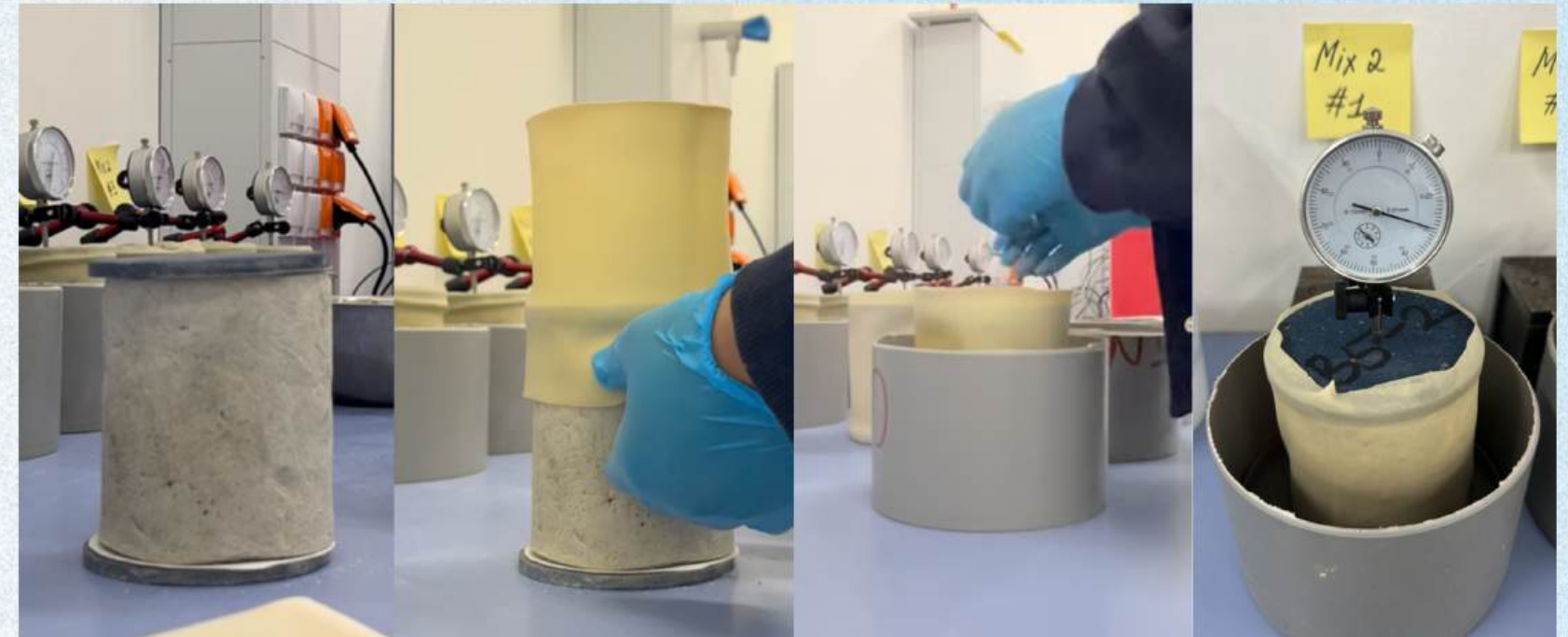


Fig 21. Sample installation procedure for the swelling test.

Mass Addition Results

Table 5. Volumetric swell for volumetric BOFS addition.

Mix	Description [BOFS particle size range]	Volumetric Swell, %	
		RBOFS(Volume) 20 %	30 %
1	SBS* only	15.76	14.70
2	SBS+BOFS [#100,60, (]	13.79	11.23
3	SBS+BOFS [#100,60,40,]	14.20	14.16
4	SBS+BOFS [#100,60,40,20,
]	17.70	16.69
5	SBS+BOFS [#100,60,40,20,10, & #4]	19.07	18.77

Table 6. Volumetric swell for mass BOFS addition.

Mix	Description [BOFS particle size range]	Volumetric Swell, %	
		RBOFS(mass) 20 %	30 %
1	SBS* only	15.76	14.70
2	SBS+BOFS [#100, #60, and #40]	12.95	9.78
3	SBS+BOFS [#100, #60, #40, and #20]	9.76	9.12
4	SBS+BOFS [#100, #60, #40, #20, and #10]	7.81	7.29
5	SBS+BOFS [#100, # 60, #40, #20, #10, and #4]	5.97	4.94

Volumetric Addition Results

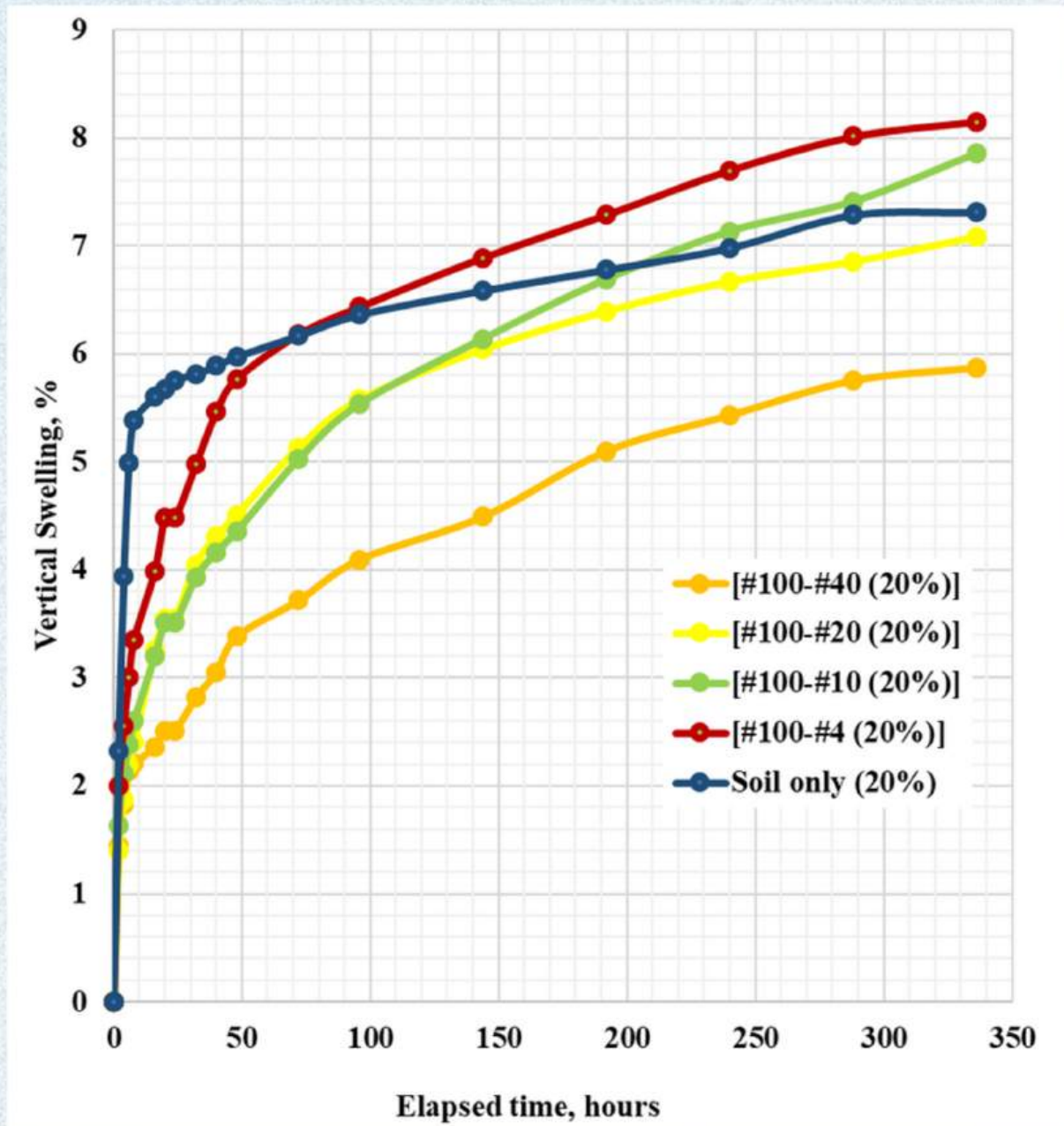


Fig 22. Vertical swell strain for RBOFS(Volume)= 20 %.

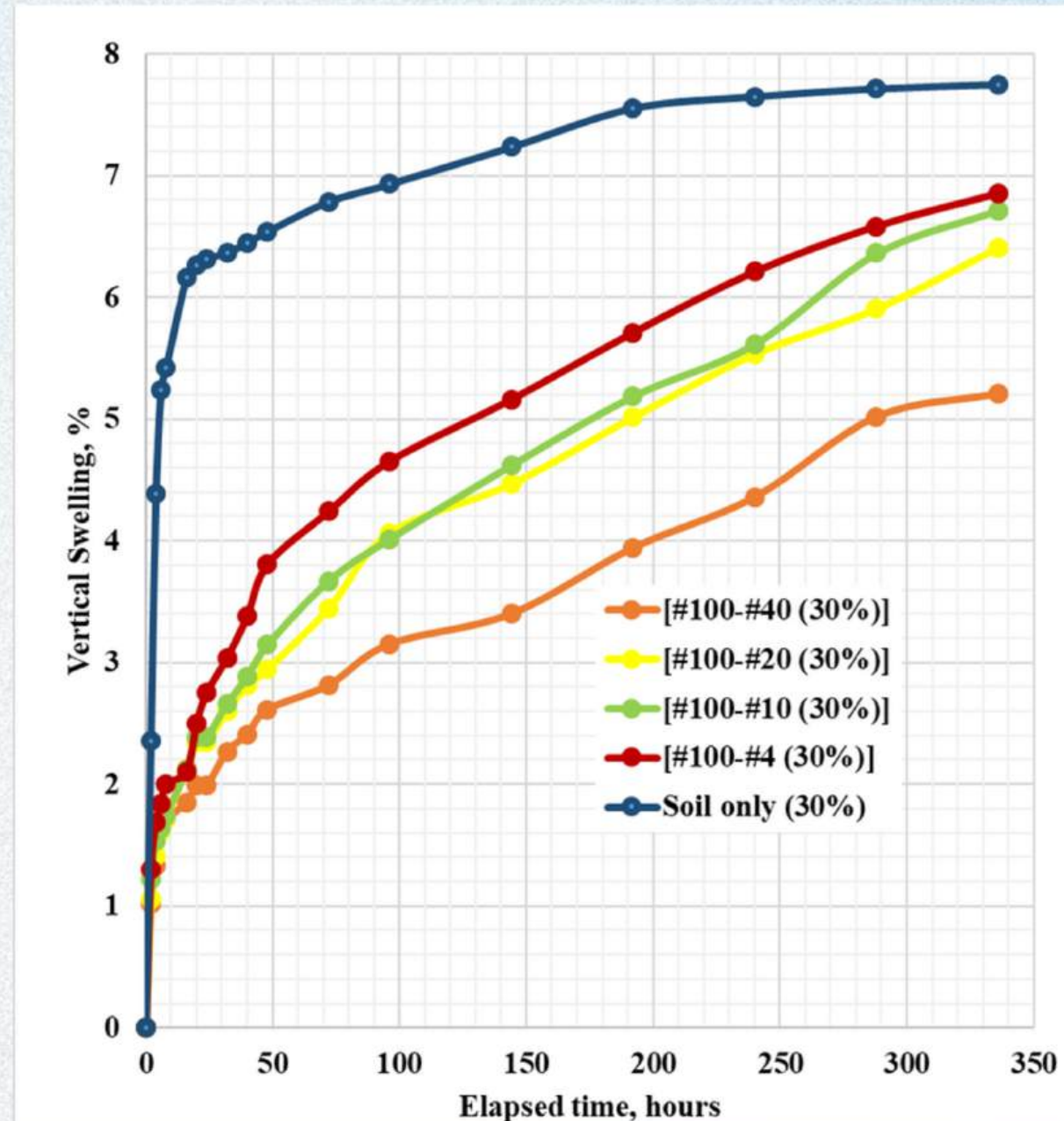


Fig 23. Vertical swell strain for RBOFS(Volume)= 30 %.



Key Observations:

- Control: Highest swell (15.76%)
- Finer BOFS (#100–#40): Best performance (11.23%)
- Coarser particles = more swelling

Mass Addition Results

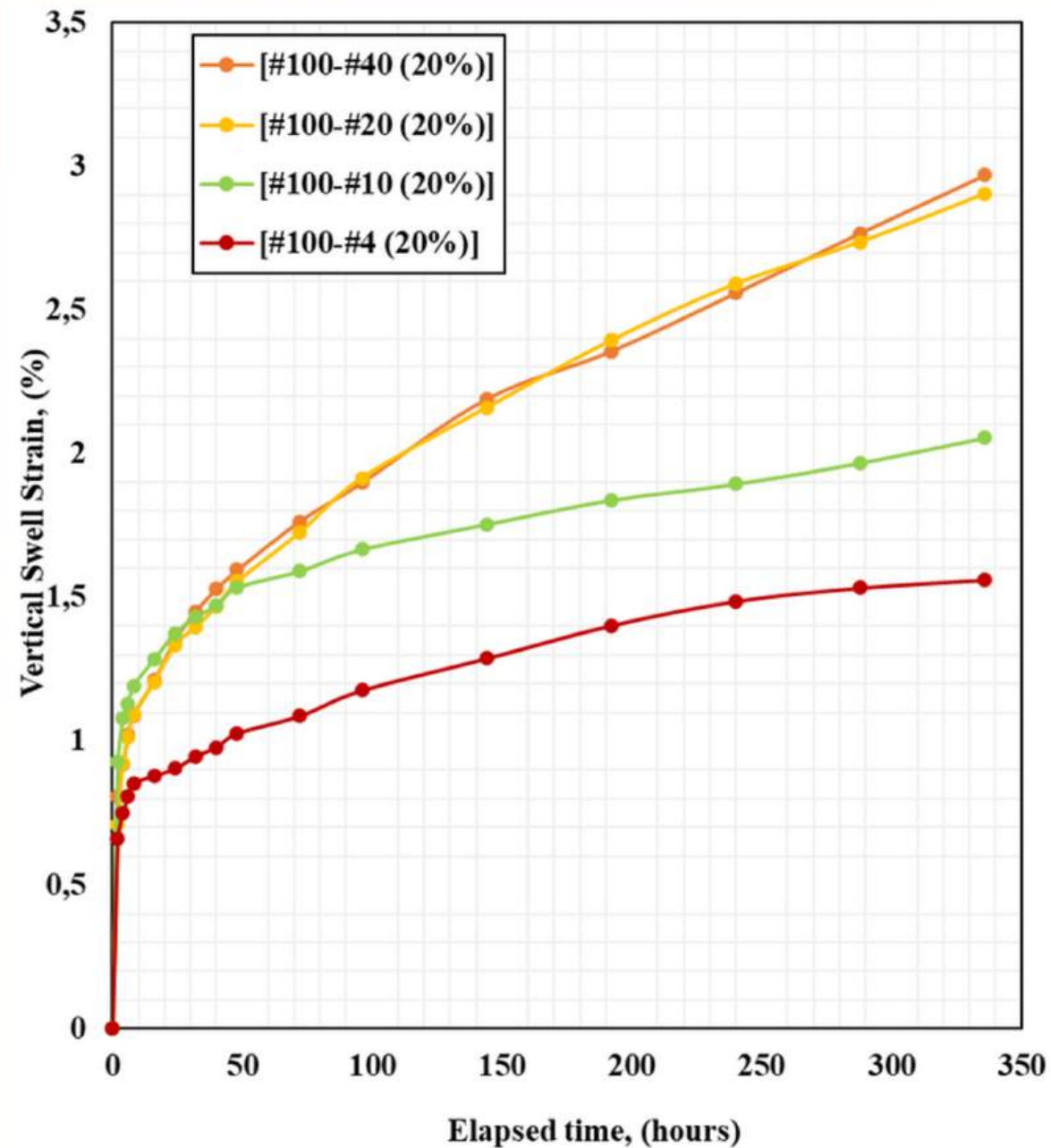


Fig 24. Vertical swell strain for RBOFS(Mass)= 20 %.

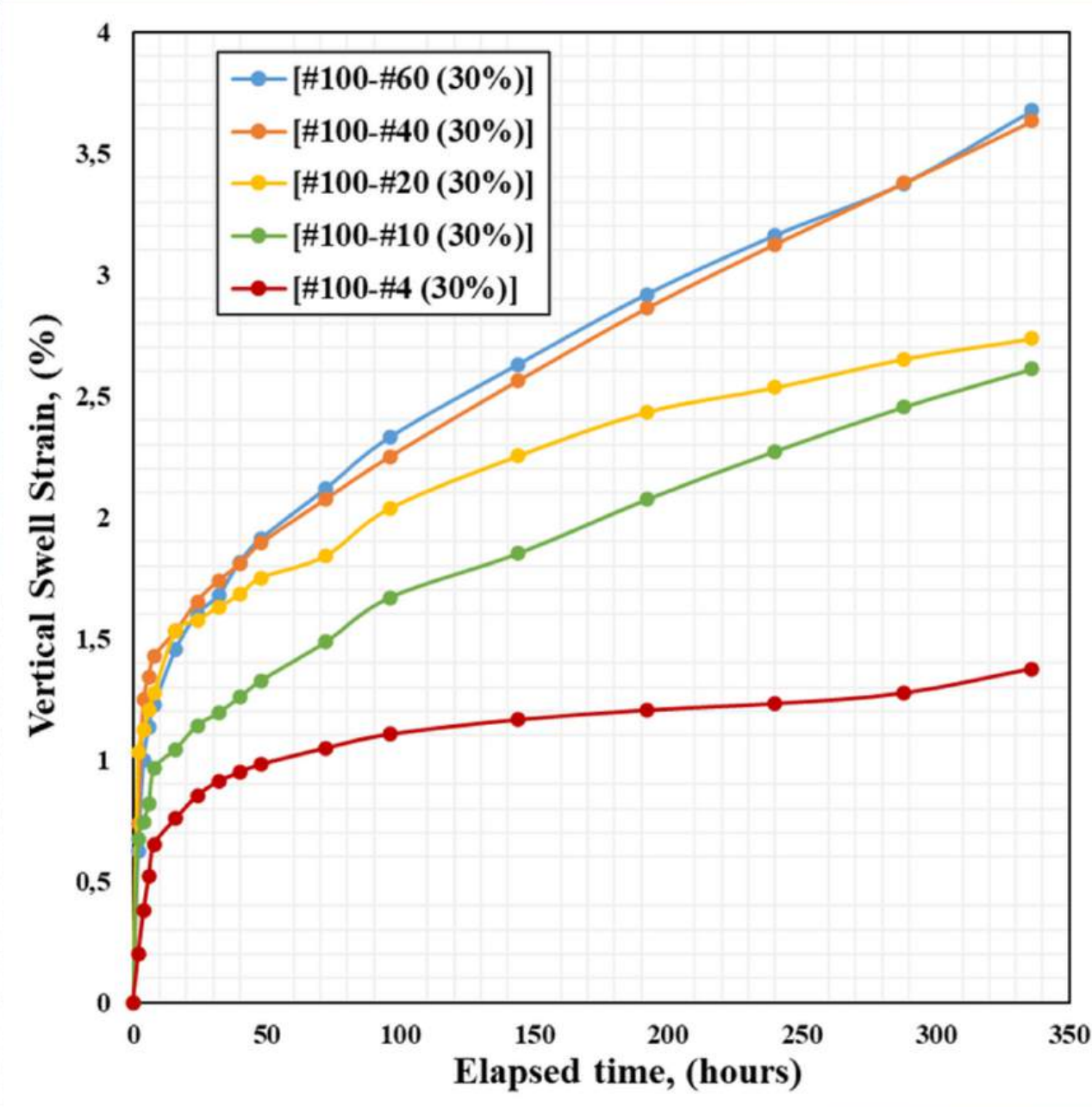


Fig 25. Vertical swell strain for RBOFS(Mass)= 30 %.



Key Observations:

- Swelling with increased BOFS mass
- Coarser BOFS (#100-#4) = Lowest swell (4.94% at 30%)
- Finer blends swelled more rapidly early on

Swelling Summary

Parameters	Impact on Swelling
Finer BOFS Particles	Reduced initial swell, but may absorb moisture fast
Coarser BOFS Particles	Best reduction in total volumetric swelling
Higher BOFS Addition	Greater swelling reduction at 30%

Mineralogical & Microstructural Analysis

Mineralogical and Microstructural Analysis – Summary

Purpose of the Analysis

- To assess how BOFS particle size and replacement rate influence:
 - Mineral formation (via XRD)
 - Microstructural behavior (via SEM + EDS)
- **Goal:** Understand how stabilization with BOFS affects swelling, bonding, and durability at the microscopic level

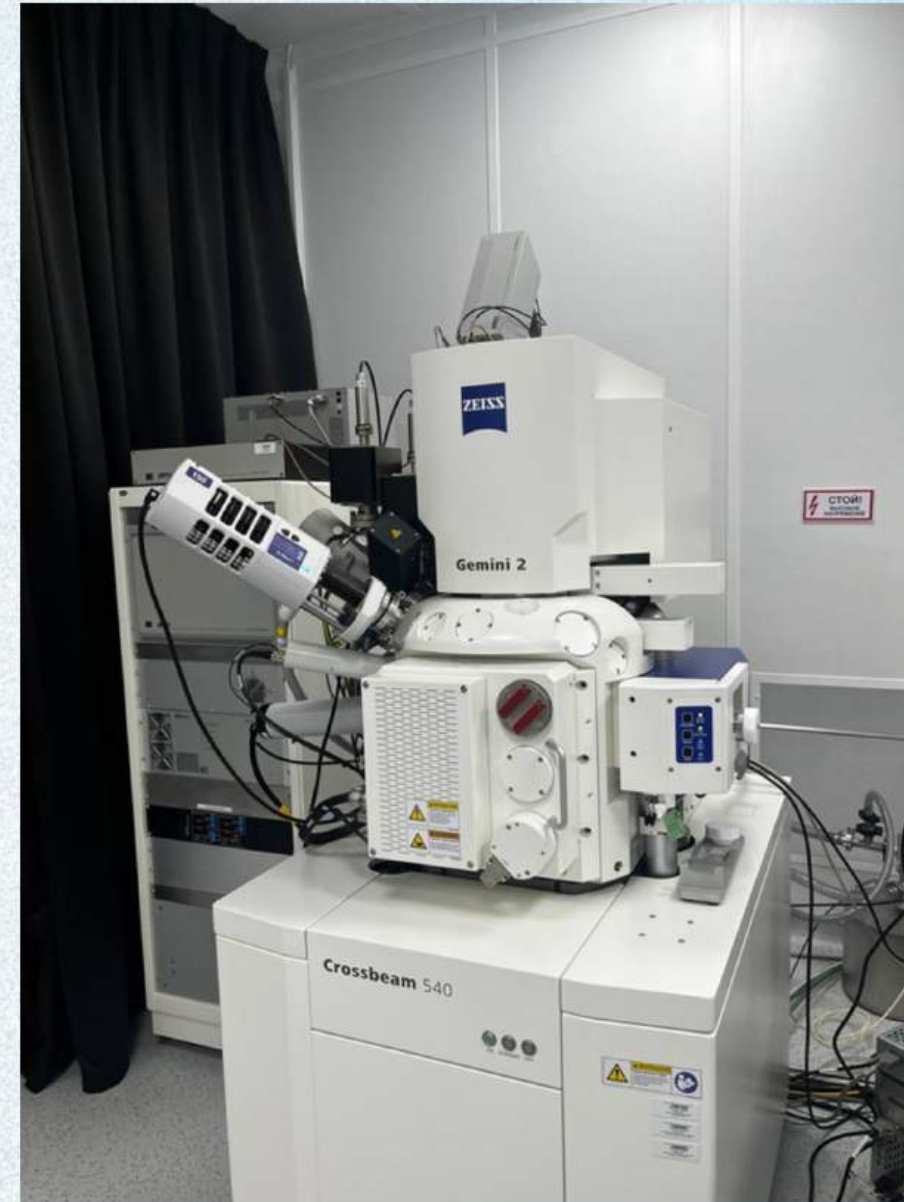


Fig 26. SEM analysis equipment.



Fig 27. XRD equipment.

XRD Analysis

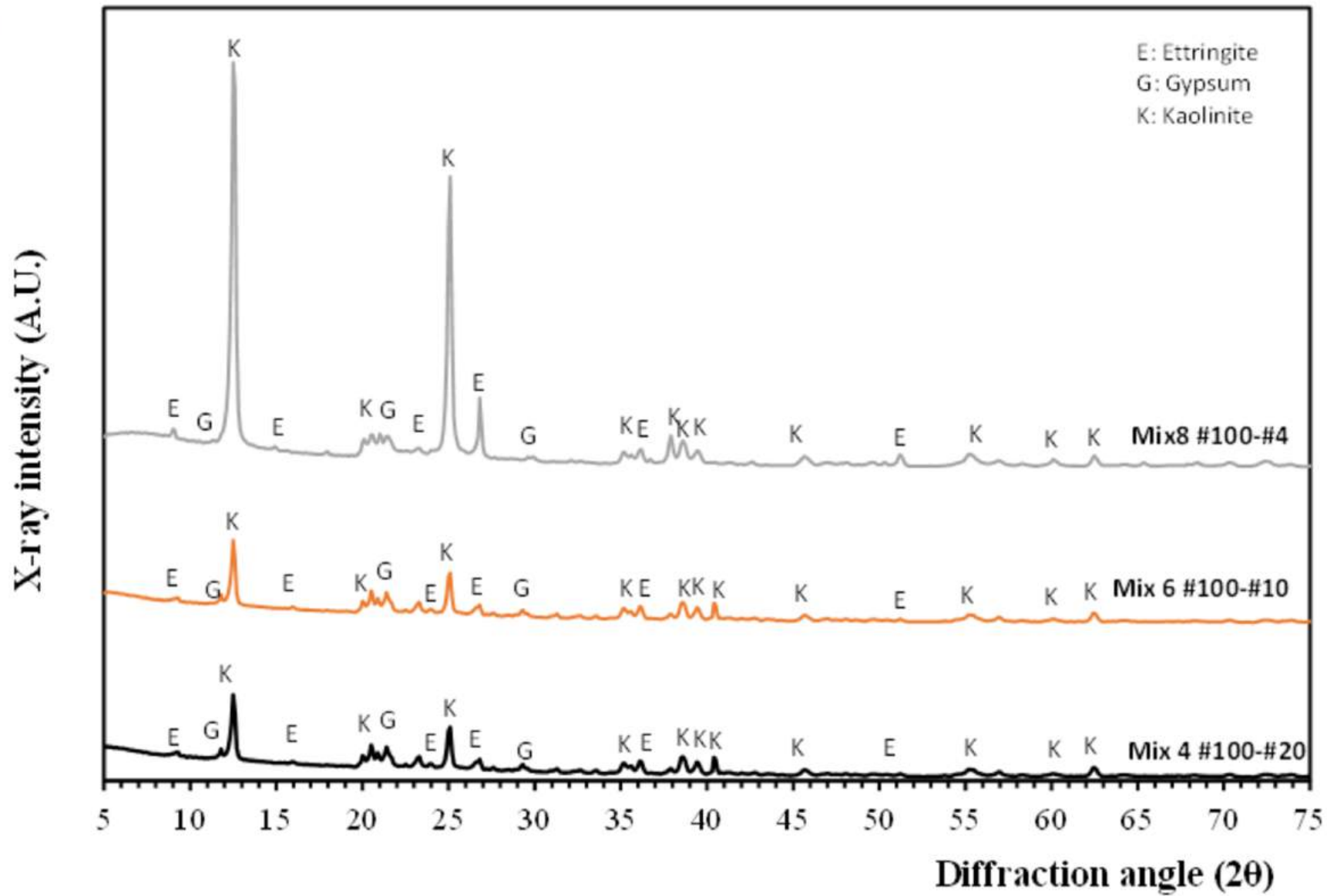


Fig 28. XRD Analyses for Mixtures (R(BOFS)(vol.)=20%) after Swelling Test

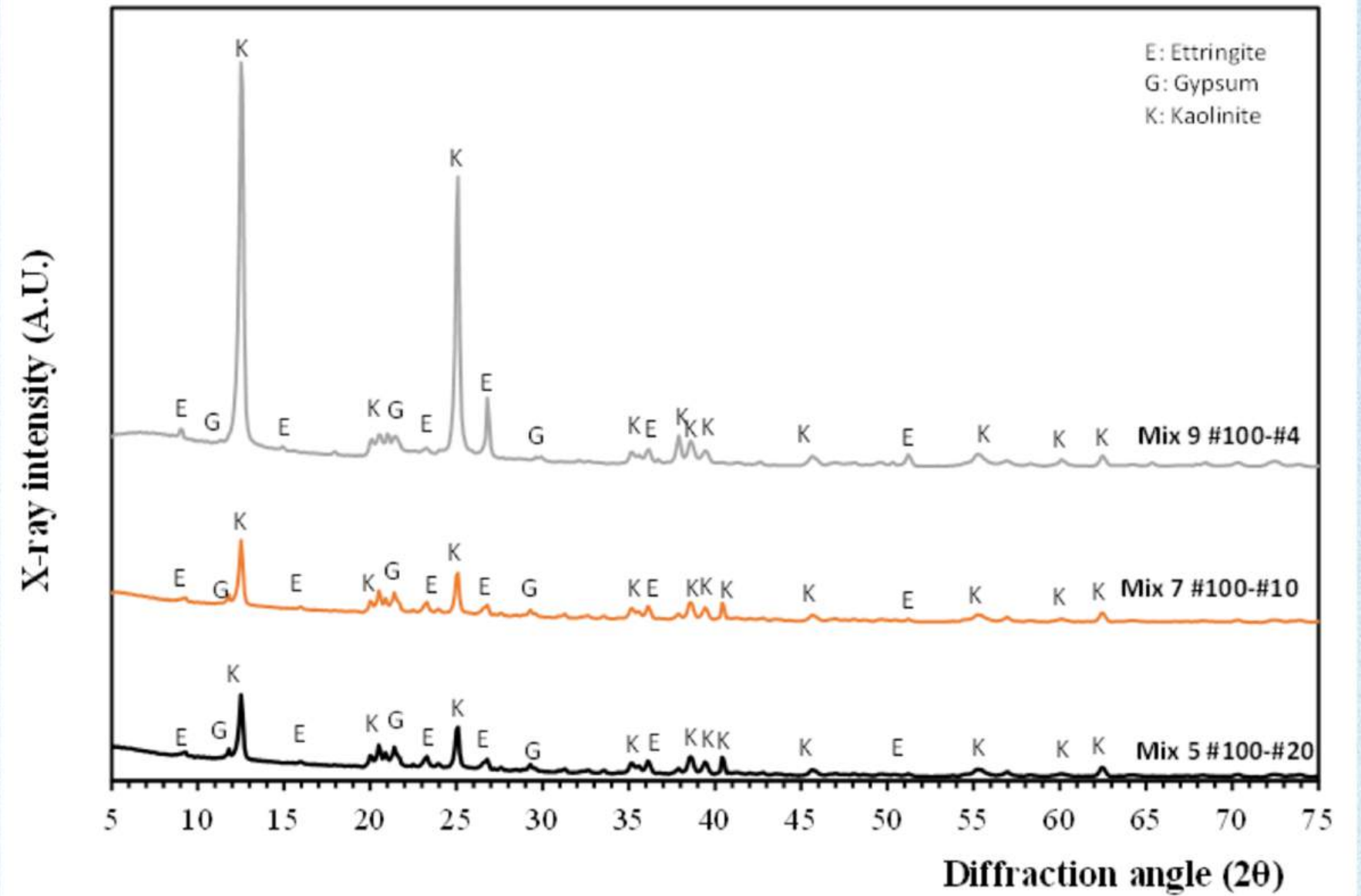


Fig 29. XRD Analyses for Mixtures (R(BOFS)(vol.)=30%) after Swelling Test

SEM Analysis - 20 %

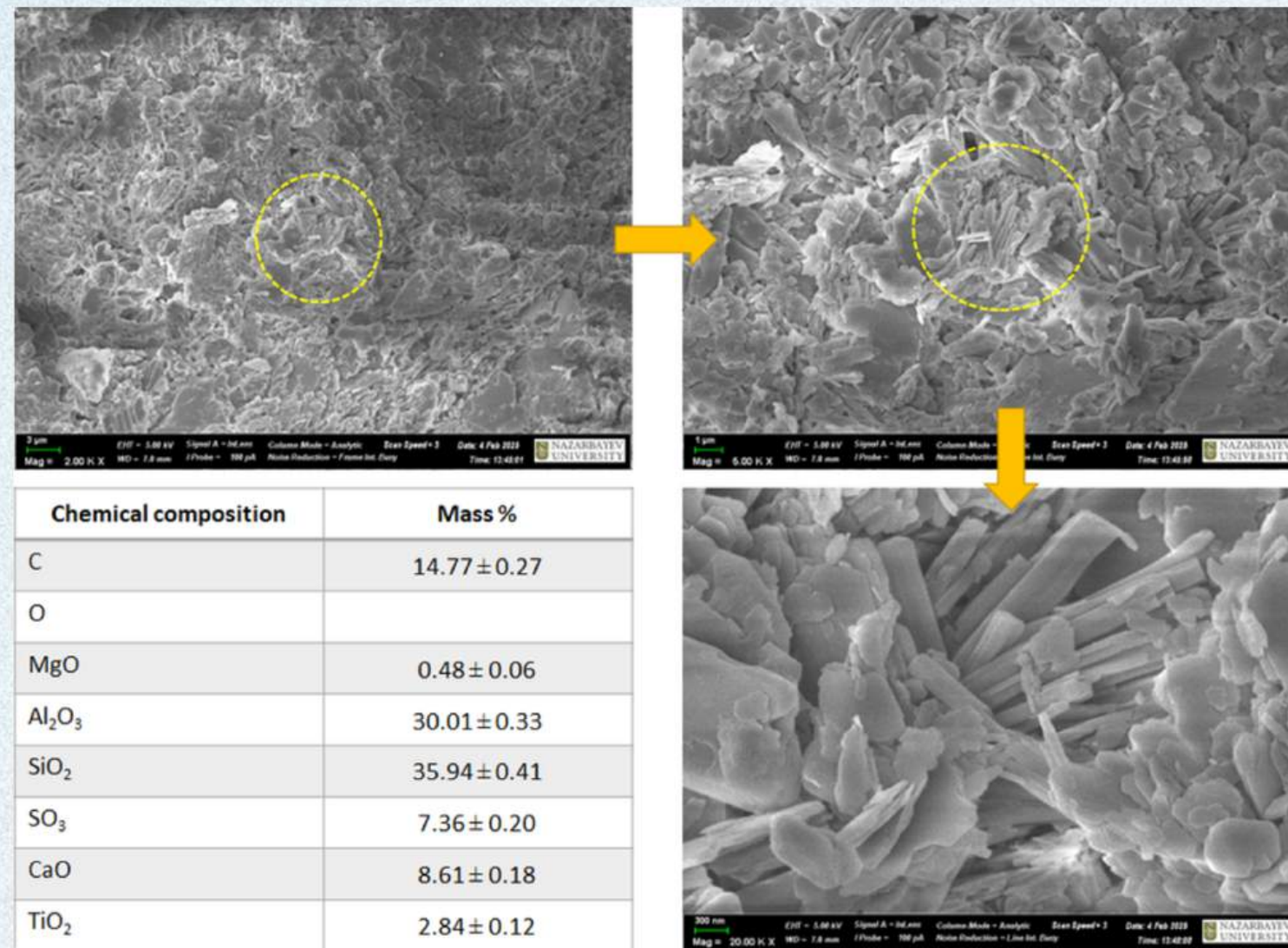


Fig 30. SEM Images for Mixtures containing #100 to #20 BOFS Particles (R= 20%) after Swelling Test.

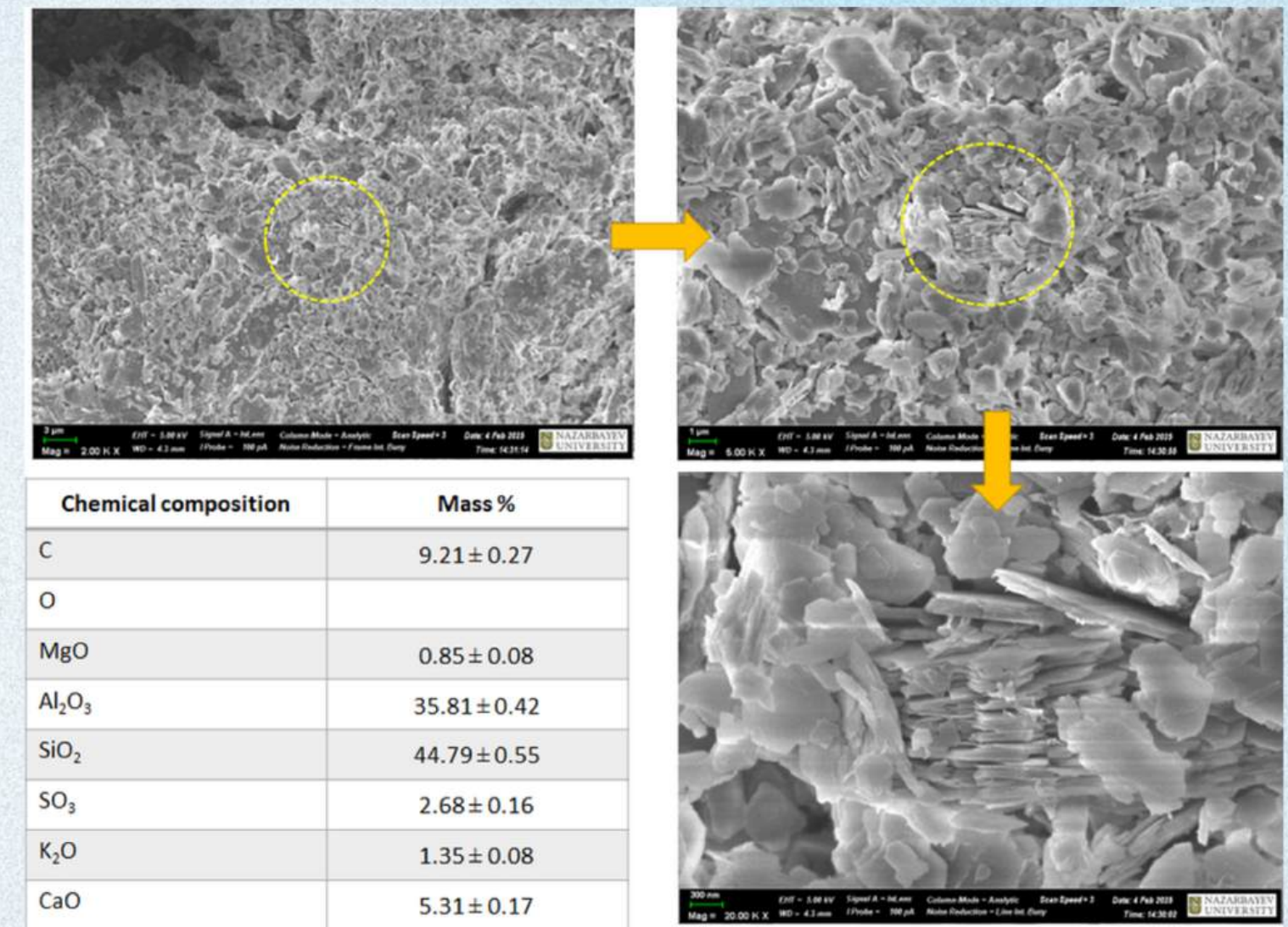


Fig 31. SEM Images for Mixtures containing #100 to #4 BOFS Particles (RBOFS(vol.)= 20%) after Swelling Test.

SEM Analysis - 30%

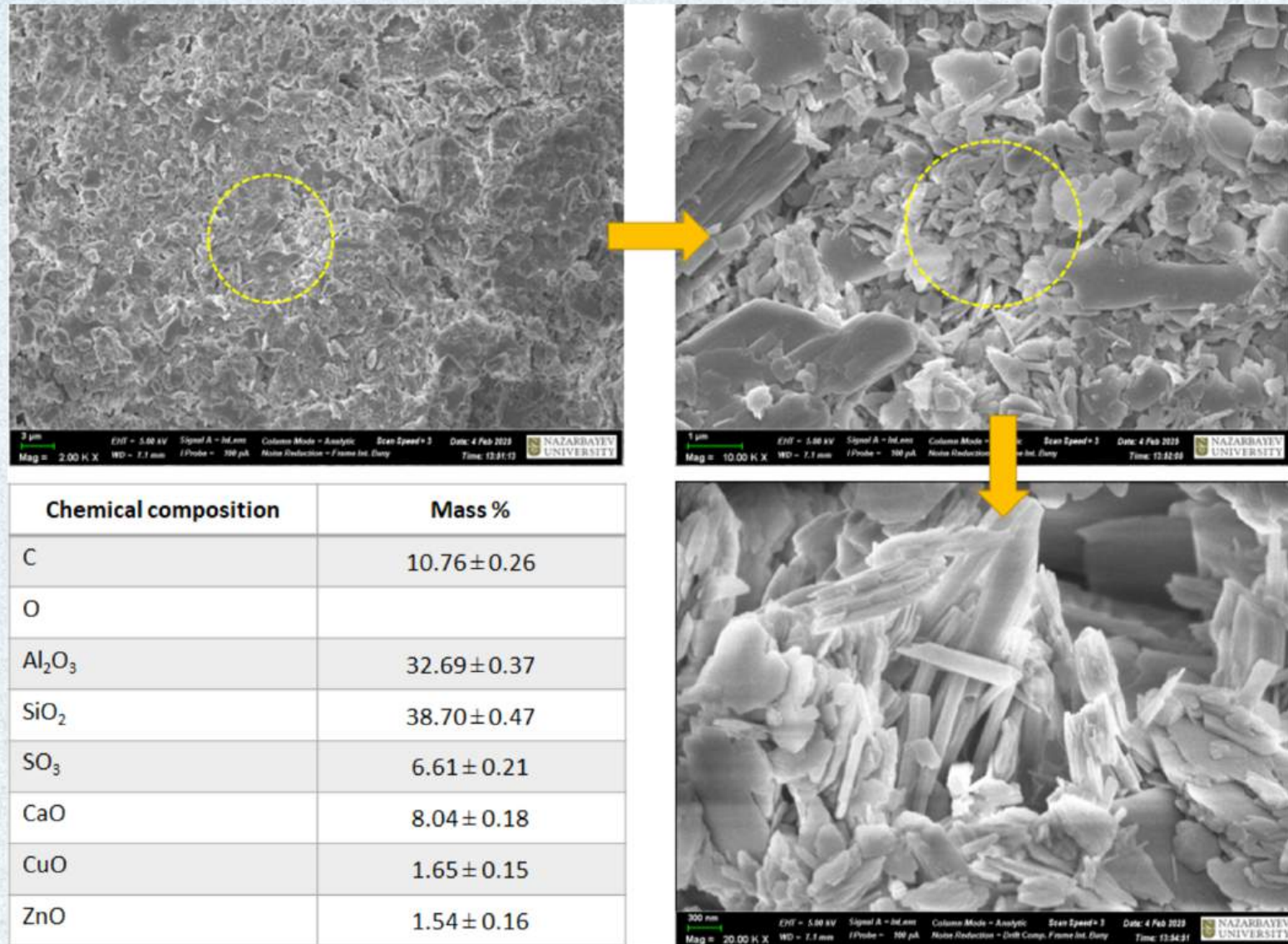


Fig 32. SEM Images for Mixtures containing #100 to #20 BOFS Particles (RBOFS(vol.)= 30%)

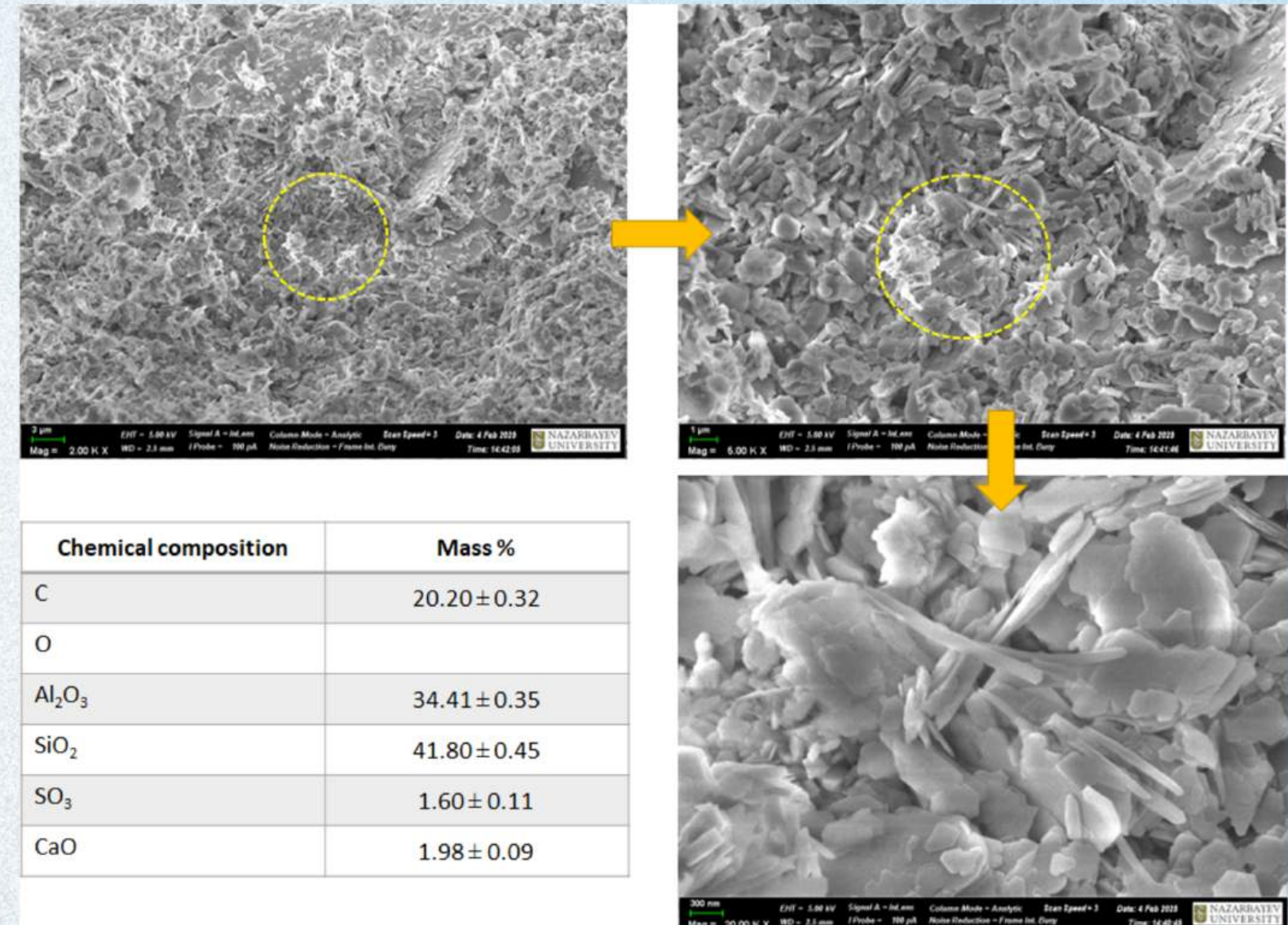


Fig 33. SEM Images for Mixtures containing #100 to #4 BOFS Particles (RBOFS(vol.)= 30%)

Conclusion: XRD and SEM Analysis Summary

Aspect	Finer BOFS Particles (#100–#20)	Coarser BOFS Particles (#100–#4)
XRD – Ettringite Peaks	Weak to moderate, controlled formation	Strong, intense – indicates higher expansion risk
XRD – Mineral Behavior	Stable mineral development	Aggressive ettringite growth
SEM – Matrix Structure	Dense, well-packed, low porosity	Loose, porous, with visible voids
SEM – Ettringite Shape	Short, thin, evenly spread needles	Long, clustered, uncontrolled crystals
EDS – CaO & SO ₃ Levels	High – supports pozzolanic and sulfate reactions	Low – reduced reactivity, but still high swelling
Stabilization Effect	Strong bonding, reduced swelling, better durability	Weak bonding, more swelling, lower durability

Strength Prediction Model

Strength Estimation Process

In their study, Cikmit et al. (2019) developed a strength prediction model for stabilized soils

1. Sieve Analysis

- BOFS particle size distribution (ASTM E11)

2. UCS Test

- Determine effective size range
- BOFS addition by volume

$$R_{BOFS(volumetric)} = \frac{V_{BOFS}}{V_{soil} + V_{water} + V_{BOFS}} \times 100 \quad (\%)$$

3. Calculate Mass Addition Rate

$$R_{BOFS(mass)} = \frac{M_{BOFS(GB)}}{M_{soil} + M_{water} + M_{BOFS}} \times 100 \quad (\%)$$

4. Calculate Specific Surface Area

$$SSA = \frac{6}{\rho} \sum_{i=1}^n \left(\frac{w_i}{x_i} \right)$$

n - the number of intervals in the grain size distribution

w_i - weight of retained fraction size i

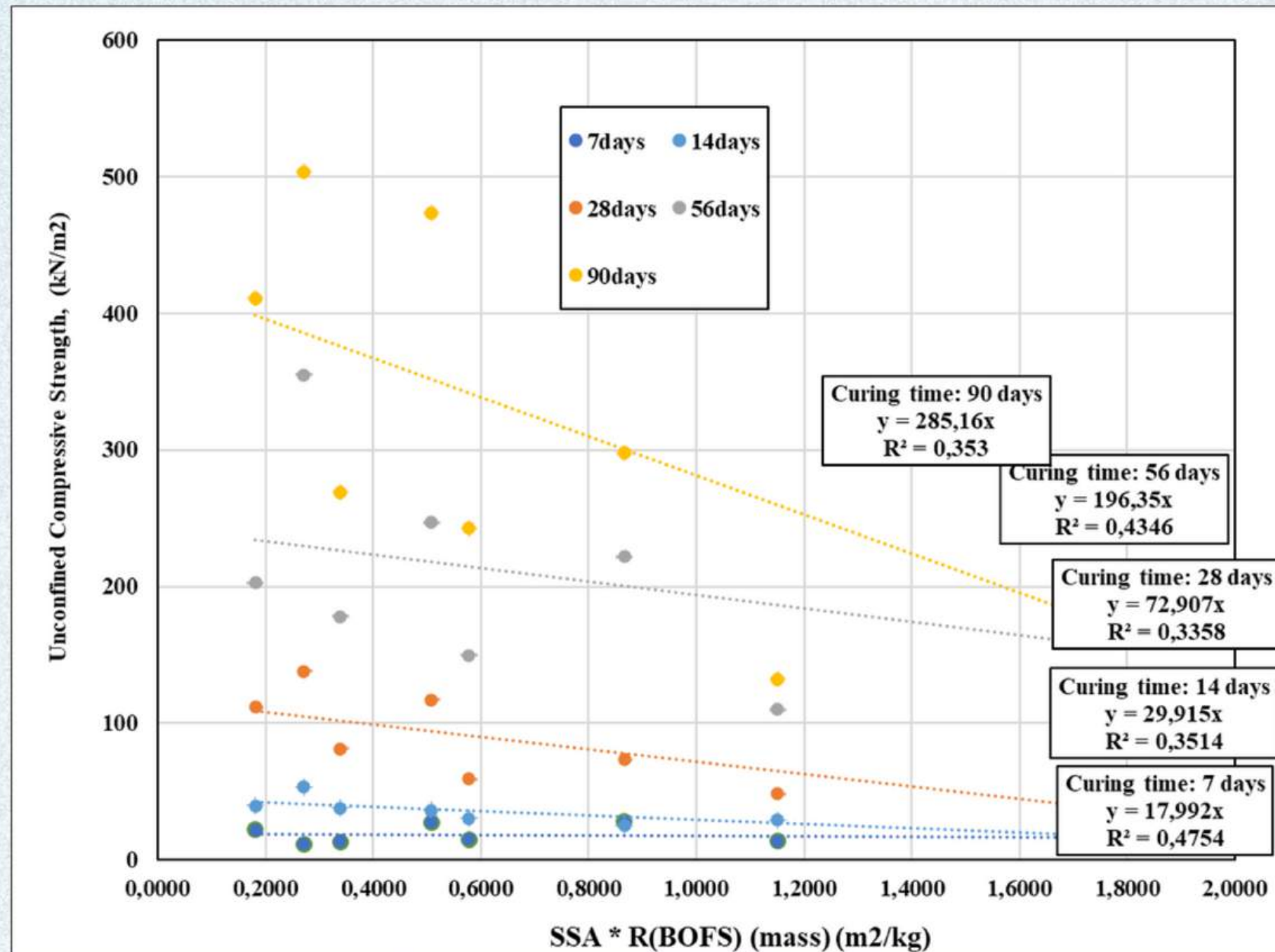
x_i - harmonic mean size distribution

ρ - density of material

Harmonic mean size distribution is calculated using the following equation below:

$$x_i = \left(\frac{(x_h^2 + x_j^2) * (x_h + x_j)}{4} \right)^{1/3}$$

UCS Prediction Model - Mass-Based



- **7 days:**

$$q_{u(7 \text{ days})} = 17.992 \times (SSA \times R_{BOFS})$$

- **14 days:**

$$q_{u(14 \text{ days})} = 29.915 \times (SSA \times R_{BOFS})$$

- **28 days:**

$$q_{u(28 \text{ days})} = 72.907 \times (SSA \times R_{BOFS})$$

- **56 days:**

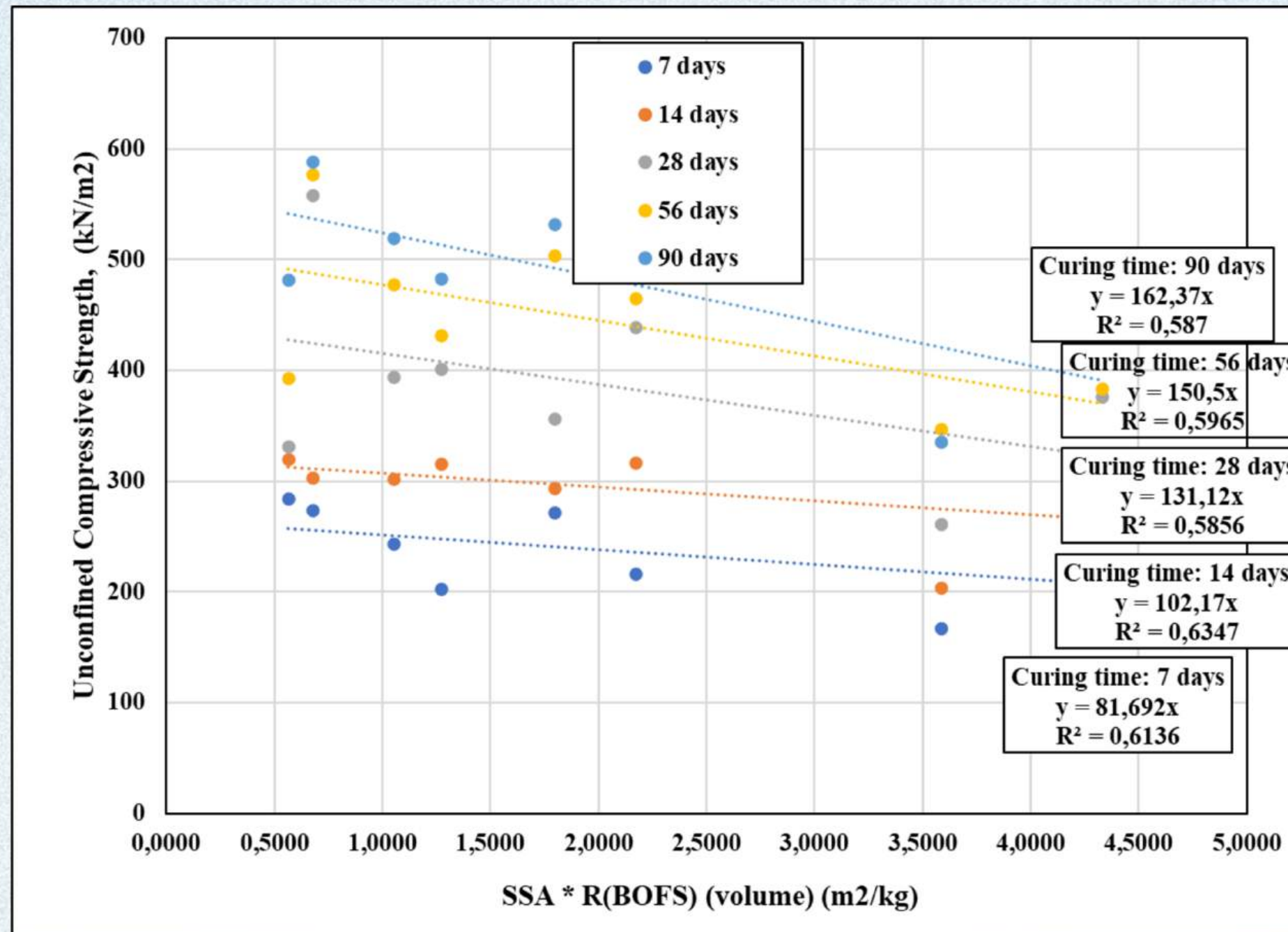
$$q_{u(56 \text{ days})} = 196.35 \times (SSA \times R_{BOFS})$$

- **90 days:**

$$q_{u(90 \text{ days})} = 285.16 \times (SSA \times R_{BOFS})$$

Fig 34. Relationship between $SSA \times R(BOFS)(mass)$ and UCS over time.

UCS Prediction Model - Volumetric



- **7-day** curing period was:
 $q_{u(7\text{ days})} = 81.692x (SSA \times R_{BOFS})$
- **14 days**
 $q_{u(14\text{ days})} = 102.17 x (SSA \times R_{BOFS})$
- **28 days**
 $q_{u(28\text{ days})} = 131.12 x (SSA \times R_{BOFS})$
- **56 days**
 $q_{u(56\text{ days})} = 150.50 x (SSA \times R_{BOFS})$
- **90 days**
 $q_{u(90\text{ days})} = 162.37 x(SSA \times R_{BOFS})$

Fig 35. Relationship between SSA × R(BOFS)(volumetric) and UCS over time.







Key Findings from Strength Prediction Model

- UCS increases linearly with $SSA \times R(\text{BOFS})$
- Curing time significantly impacts strength gain, especially after 28 days.
- Mass-based model gives a slightly better fit for long-term strength prediction.
- Volume-based model is more sensitive at early ages and practical for on-site mixing.
- Both models are valid and reliable, with regression equations enabling strength forecasting.

Conclusion – Summary of Key Findings

- Finer BOFS particles significantly improved UCS due to greater surface area and enhanced pozzolanic activity.
- Curing time was crucial; 90-day samples showed the highest strength gain.
- Swelling tests revealed that BOFS effectively reduced expansion, especially with finer particles.
- XRD and SEM analyses confirmed ettringite formation and the presence of cementitious products like C-S-H and C-A-H
- BOFS shows strong potential as a sustainable alternative stabilizer, promoting waste reuse and durability in sulfate-rich soils.

Future Works – Research Directions

-  Include comparative studies using traditional stabilizers (e.g., lime, cement) alongside BOFS.
-  Explore hybrid mixtures combining BOFS with GGBFS, fly ash, or cement.
-  Test intermediate BOFS addition rates (e.g., 10%, 15%, 25%, 35%) to better define optimal range.
-  Extend curing periods beyond 90 days to evaluate long-term durability and pozzolanic evolution.
-  Analyze 40% BOFS mixtures, especially in swelling studies where it showed secondary performance.
-  Scale up field applications to validate lab results under real environmental condition



**Thank
You**

References

- [1] Talluri, N. (2013a). Stabilization of High Sulfate Soils [Doctoral Dissertation, The University of Texas at Arlington]. Nagasreenivasu Talluri. Retrieved from https://rc.library.uta.edu/uta-ir/bitstream/handle/10106/23923/Talluri_uta_2502D_12312.pdf?sequence=1&isAllowed=y
- [2] Knopp, R., & Moormann, C. (2016). Improving the Performance of Sulfate-Bearing Clays by Using Industrial Waste Products. *Journal of Geotechnical and Geoenvironmental Engineering*, 142(6), 1-12.
- [3] Brand, A. S., Singhvi, P., Fanijo, E. O., & Tutumluer, E. (2020). Stabilization of a Clayey Soil with Ladle Metallurgy Furnace Slag Fines. *Materials*, 13 (4251): 1-19. <https://doi.org/10.3390/ma13194251>
- [4] Diniz, H.D., Carvalho, M.J., Mendes, C.J., & Peixoto, A.R. (2017). Blast Oxygen Furnace Slag as Chemical Soil Stabilizer for Use in Roads. *Journal of Materials in Civil Engineering*, 29(4), 1-9.
- [5] Mustafayeva, A., Bimykova, A., Olagunju, S. O., Kim, J., Satyanaga, A., & Moon, S.-W. (2023). Mechanical properties and microscopic mechanism of basic oxygen furnace (BOF) slag-treated clay subgrades. *Buildings*, 13(12), 2962. <https://doi.org/10.3390/buildings13122962>
- [6] Abdi, M.R. (2011). Effects of basic oxygen steel slag (BOS) on strength and durability of kaolinite. *International Journal of Civil Engineering*, 9(2)
- [7] Biggs, A.J.W., & Mahony, K. M. (2004). Is Soil Science Relevant to Road Infrastructure? International Soil Conservation Organization Conference, Brisbane, Australia.
- [8] Adams, T. (2021, June 29). What is Soil Stabilization? Industry articles. Retrieved September 8th, 2023, from <https://globalroadtechnology.com/what-is-soil-stabilization/>
- [9] McCarthy, F.J., & McKay, D.L. (2009). Colloid transport in the subsurface: Past, present, and future challenges. *Vadose Zone Journal*, 3(2), 326-337. <https://doi.org/10.2136/vzj2004.0326>
- [10] Firoozi, A.A., Olgun, C.G., & Baghini, S.M. (2017). Fundamentals of soil stabilization. *International Journal of Geo-Engineering*, 8(26), 1-12. <https://doi.org/10.1186/s40703-017-0064-9>
- [11] New Steel Construction (NSC). (2017, September 7). An introduction to steelmaking. <https://www.newsteelconstruction.com/wp/an-introduction-to-steelmaking/>
- [12] Naidu, S.T., Sheridan, C.M., & Dyk, L.Z. (2020). Basic oxygen furnace slag: Review of current and potential uses. *Minerals Engineering*, 149(106234). <https://doi.org/10.1016/j.mineng.2020.106234>
- [13] Teir, S., Eloneva, S., Fogelholm, C., & Zevenhoven, R. (2007). Dissolution of steelmaking slags in acetic acid for precipitated calcium carbonate production. *Energy*, 32(4), 528–539. <https://doi.org/10.1016/j.energy.2006.06.023>
- [14] Riley, A.L., & Mayes, W.M. (2015). Long-term evolution of highly alkaline steel slag drainage waters. *Environmental Monitoring Assessment*, 187(463). <https://doi.org/10.1007/s10661-015-4693-1>
- [15] Proctor, M.D., Shay, C.E., Fehling, A.K., & Finley, L. (2000). Assessment of human health and ecological risks posed by the uses of steel-industry slags in the environment. *Human and Ecological Risk Assessment: An International Environment*, 8(4), 681-711. <https://doi.org/10.1080/20028091057150>
- [16] Cikmit, A.A., Tsuchida, T., Kang, G., Hashimoto, R., & Honda, H. (2019). Particle-size effect of basic oxygen furnace steel slag in the stabilization of dredged marine clay. *Soils and Foundations*, 59(2019), 1385-1398. <https://doi.org/10.1016/j.sandf.2019.06.013>
- [17] Talafha, S. M., Oldal, I., & Garneoui, S. (2020). Study the particle size impact on the mechanical behaviour of granular material by discrete element method. *FME Transactions*, 50(3), 473-483. <https://doi.org/10.5937/fme2203473T>
- [18] Jamo, U.H., & Abdu, S.G. (2014). Structural analysis and surface morphology of kaolin. *Science World Journal*, 9(3). Available at: www.scienceworldjournal.org
- [19] Ojo, G.P., Igbokwe, U.G., Egbuachor, C.J., & Nwozor, K.K. (2017). Geotechnical properties and geochemical composition of kaolin deposits in parts of Ifon, southwestern Nigeria. *American Journal of Engineering Research*, 6(3), 15-24.
- [20] Mohammad, A.A., Al-Ajamee, M., Kobbail, A., Dahab, H., Abdo, M.M., & Alhassan, H., (2022). A study on soil stabilization for some tropical soils. *Materials Today: Proceedings*, 60: 87-92. <https://doi.org/10.1016/j.matpr.2021.12.260>