Low-calcium Slag cement: A potential solution to promote circular economy in the management of copper mine tailings

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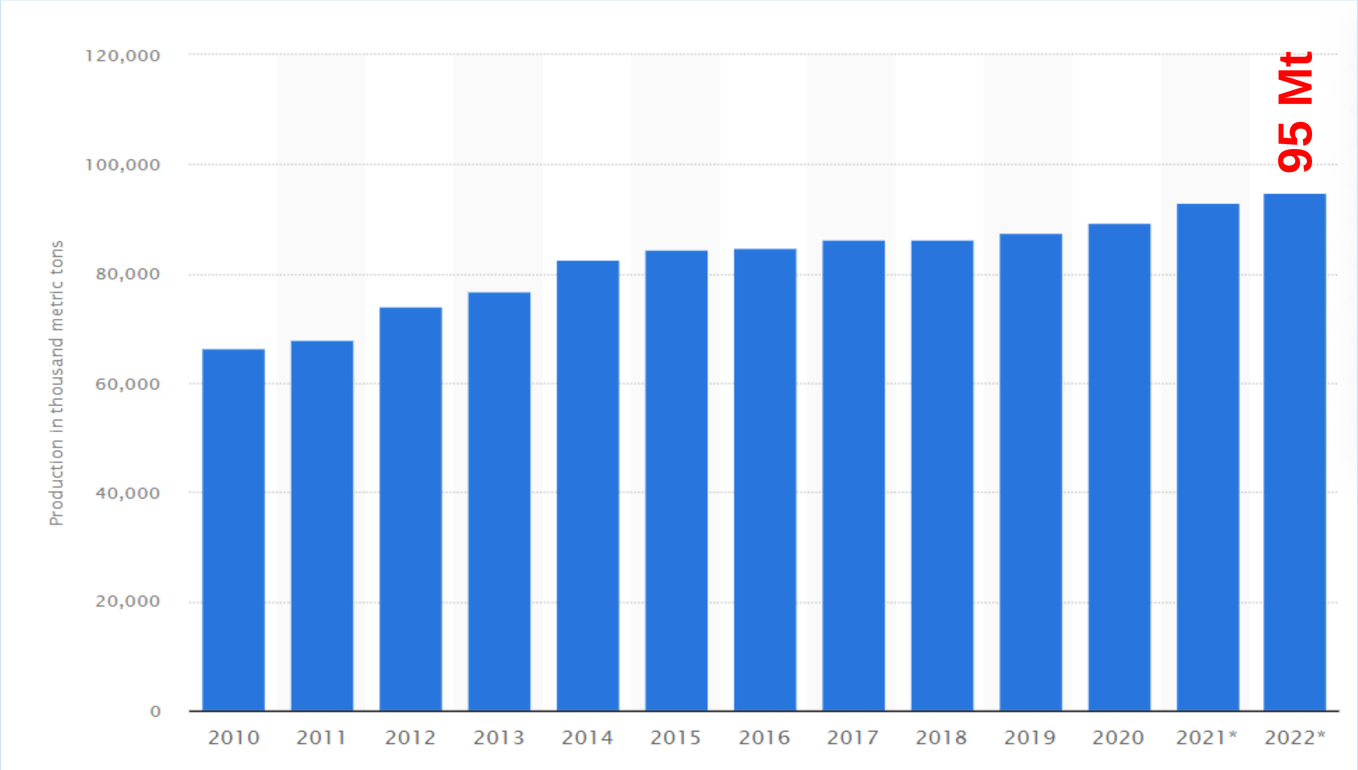
INTRODUCTION

Population growth and urban development have led to a significant increase in demand for ordinary Portland cement (OPC) in recent years (Celik et al. 2019)

INTRODUCTION

Production volume of Portland and masonry cement in the United States from 2010 to 2022



Graph taken from: https://www.statista.com/statistics/219329/us-production-of-portland-and-masonery-cement/#:~:text=In%202022%2C%20an%20estimated%2095,produced%20in%20the%20United%20States.

INTRODUCTION

1.5 ton raw materials

1 ton OPC

1 ton CO_2

Cement industry is responsible for 8% of all CO_2

INTRODUCTION

Mining industry produces large amount of mine waste every year

- **1.6 billion metric tons of mineral processing waste are produced each year in the United States.**
- **Copper smelting and refining facilities produce 2.5 million metric tons (MT) of smelter slag and 1.5 million MT of slag tailings per year.**

Image taken from http://atcwilliams.com/projects/mt-rawdon-gold-mine

Image taken from http://www.clui.org/ludb/site/sierrita-copper-mine

Environmental problems associated with tailing deposits:

- ❑ Slumps, landslides.
- ❑ Dust.
- ❑ Leaching

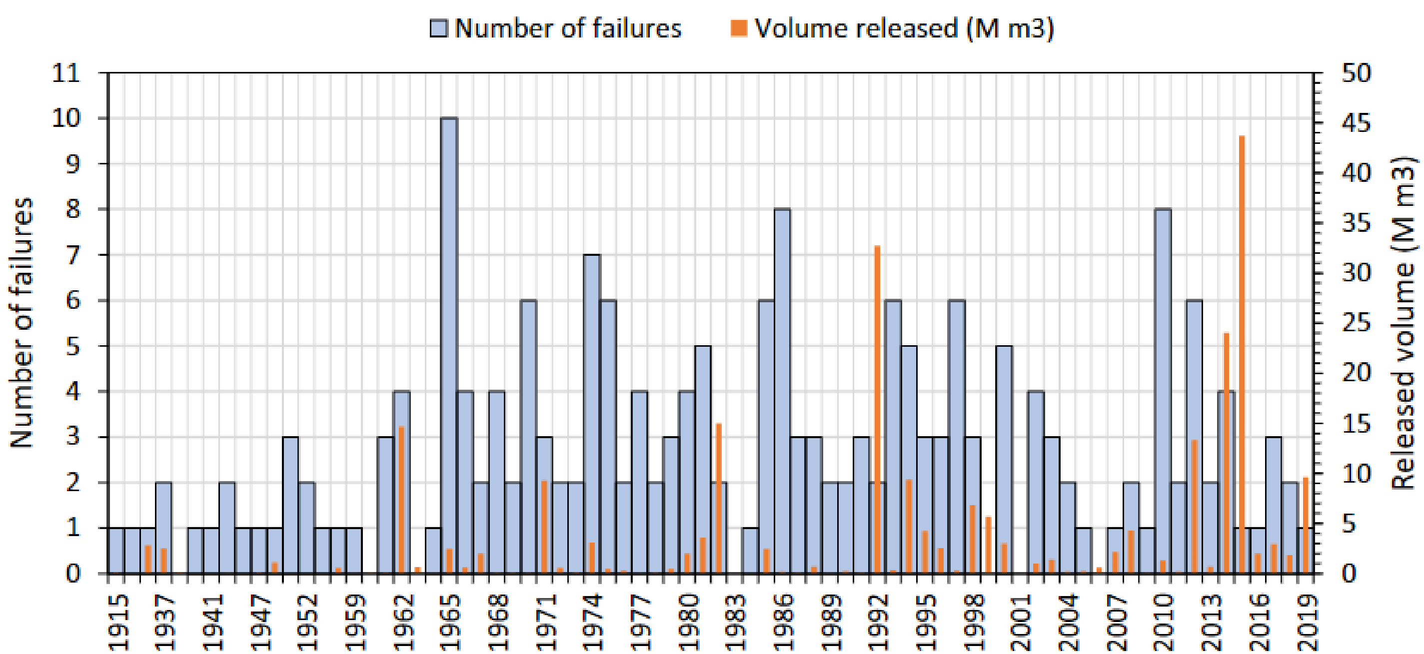


Fig. 2. Number of failures (left axis, blue columns) and volumes released (right axis, red columns) per year since 1915. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Piciullo, L., Storrøsten, E. B., Liu, Z., Nadim, F., & Lacasse, S. (2022). A new look at the statistics of tailings dam failures. *Engineering Geology*, *303*, 106657.

INTRODUCTION

Economy

- Promoting the use of tailings as construction material

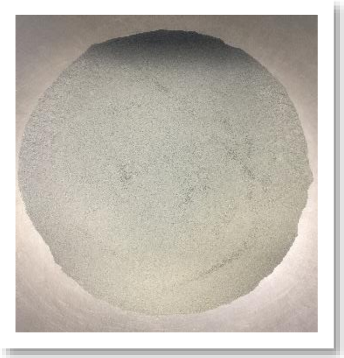
Ecology

- Unique stabilization technology called *Geopolymerization*

INTRODUCTION

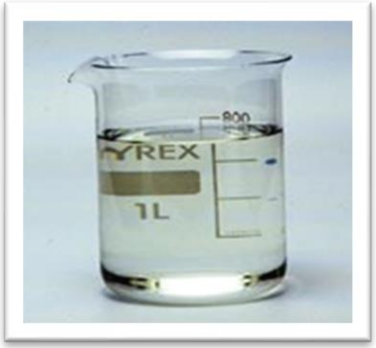
What is geopolymerization?

INTRODUCTION



Material rich in silica and alumina

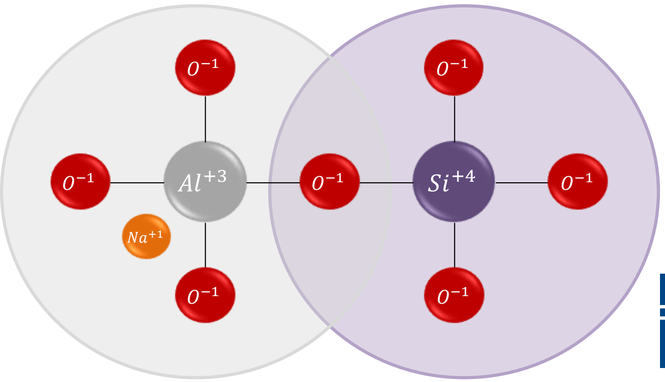
Alkaline reagent



Water

Geopolymer paste

Geopolymerization process transforms aluminosilicate materials through chemical reaction with an alkali solution into a useful product called geopolymer



INTRODUCTION

Geopolymerization

- Abundant raw material resources
- Rapid development of mechanical strength
- Immobilization of toxic and hazardous materials
- Significant reduction of energy consumption and greenhouse gas emissions

INTRODUCTION

Photo taken from: https://civiltoday.com/civil-engineering-materials/brick/69-characteristics-and-qualities-of-good-bricks-for-construction

INTRODUCTION

- Bricks have been widely used as a major construction and building material for a long time.
- Conventional production methods have several disadvantages:
  - ✓ *mining operations are energy intensive, destroy the landscape, and produce large amount of waste*.
  - ✓ *High temperature kiln firing consumes huge amount of energy, and releases large quantity of CO_2 to the atmosphere*.
  - ✓ *Natural resources like clay is limited worldwide which needs to be protected.*

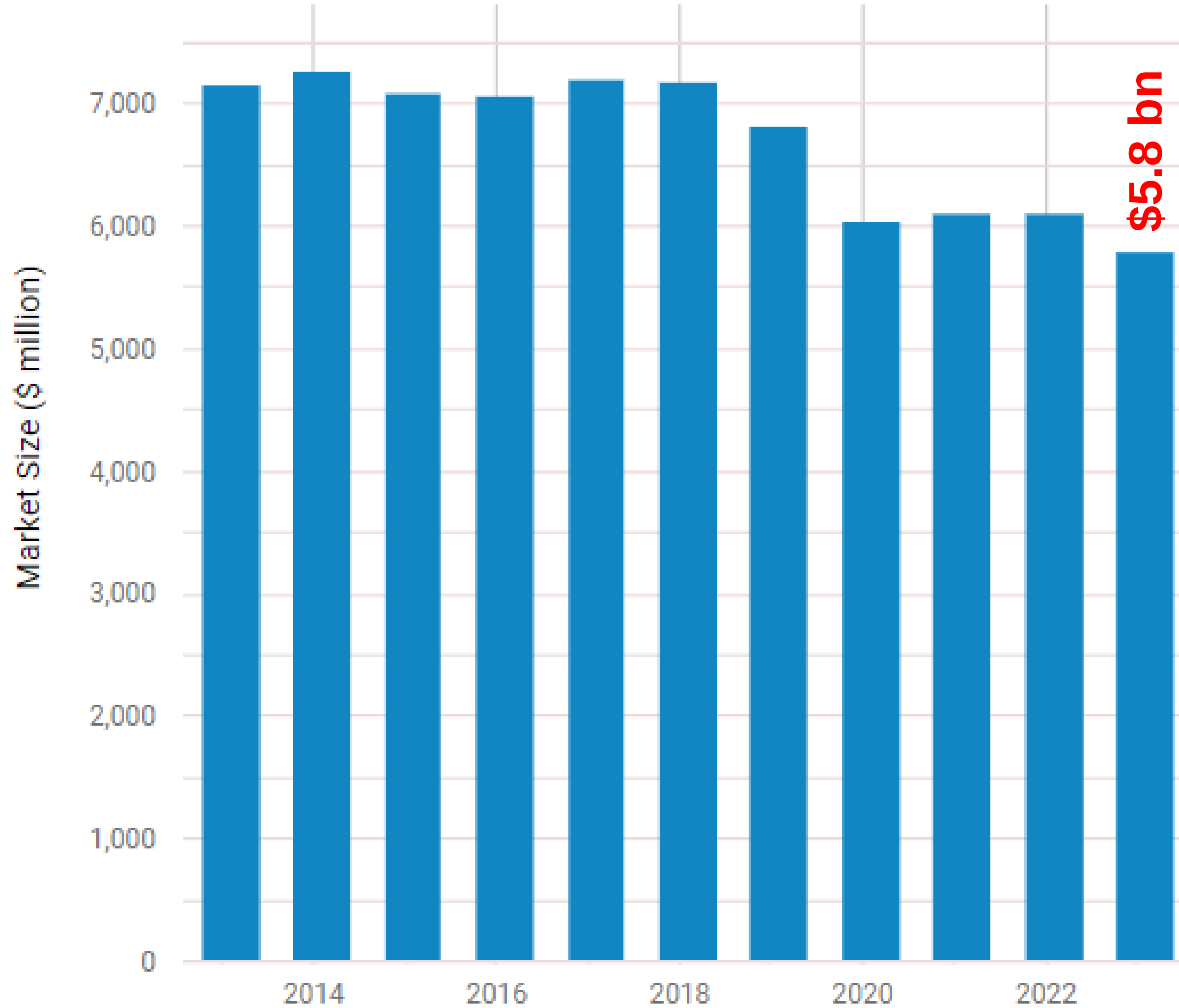
Photo taken from https://ceramics.org/ceramic-tech-today/construction/the-many-types-of-bricks

Photo taken from https://www.quora.com/What-is-the-standard-size-of-Indian-brick

THE UNIVERSITY OF ARIZONA

INTRODUCTION

Clay Brick & Product Manufacturing in the US:
Market Size 2013-2023
(Measured by revenue)



Plot taken from: https://www.ibisworld.com/industry-statistics/market-size/clay-brick-product-manufacturing-united-states/#:~:text=The%20market%20size%2C%20measured%20by,is%20%245.8bn%20in%202023.

INTRODUCTION

Geopolymer based Bricks

ASTM specifications for different applications of bricks is:

- ✓ Min UCS: 20.7 MPa
- ✓ Max water absorption: 16%

RESEARCH APPROACH

Macro-Scale Study

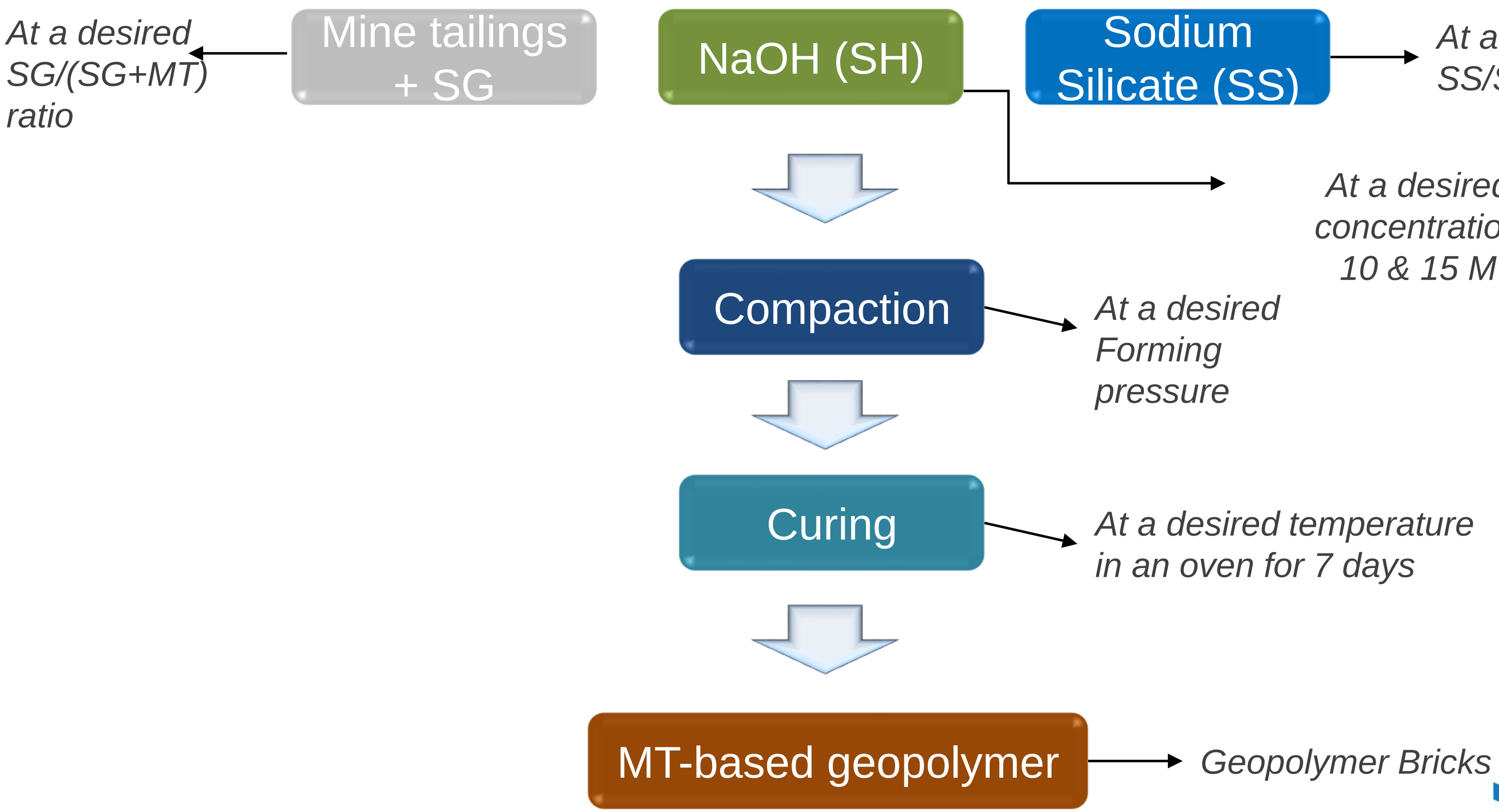
- Uniaxial Compression test
- Water Absorption test
- Wet-Dry Cycles test
- Freeze-Thaw test
- Leaching test

Micro/Nano-Scale Study

- SEM imaging
- EDS analysis
- XRD characterization
- XRF analysis

Production of geopolymer bricks

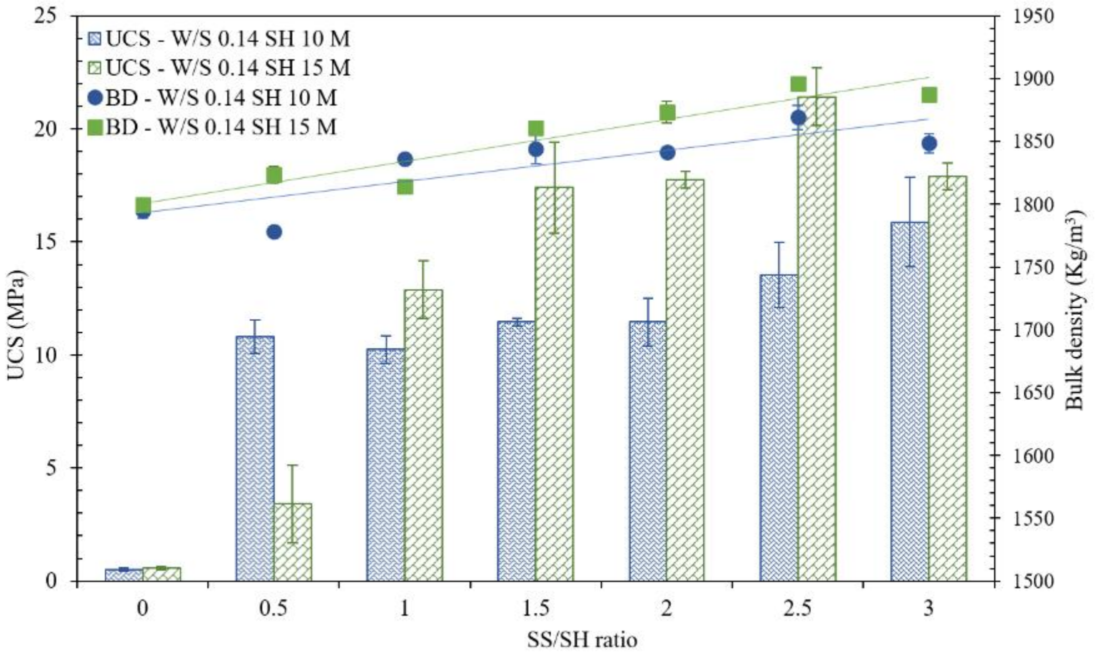
SPECIMEN PREPARATION

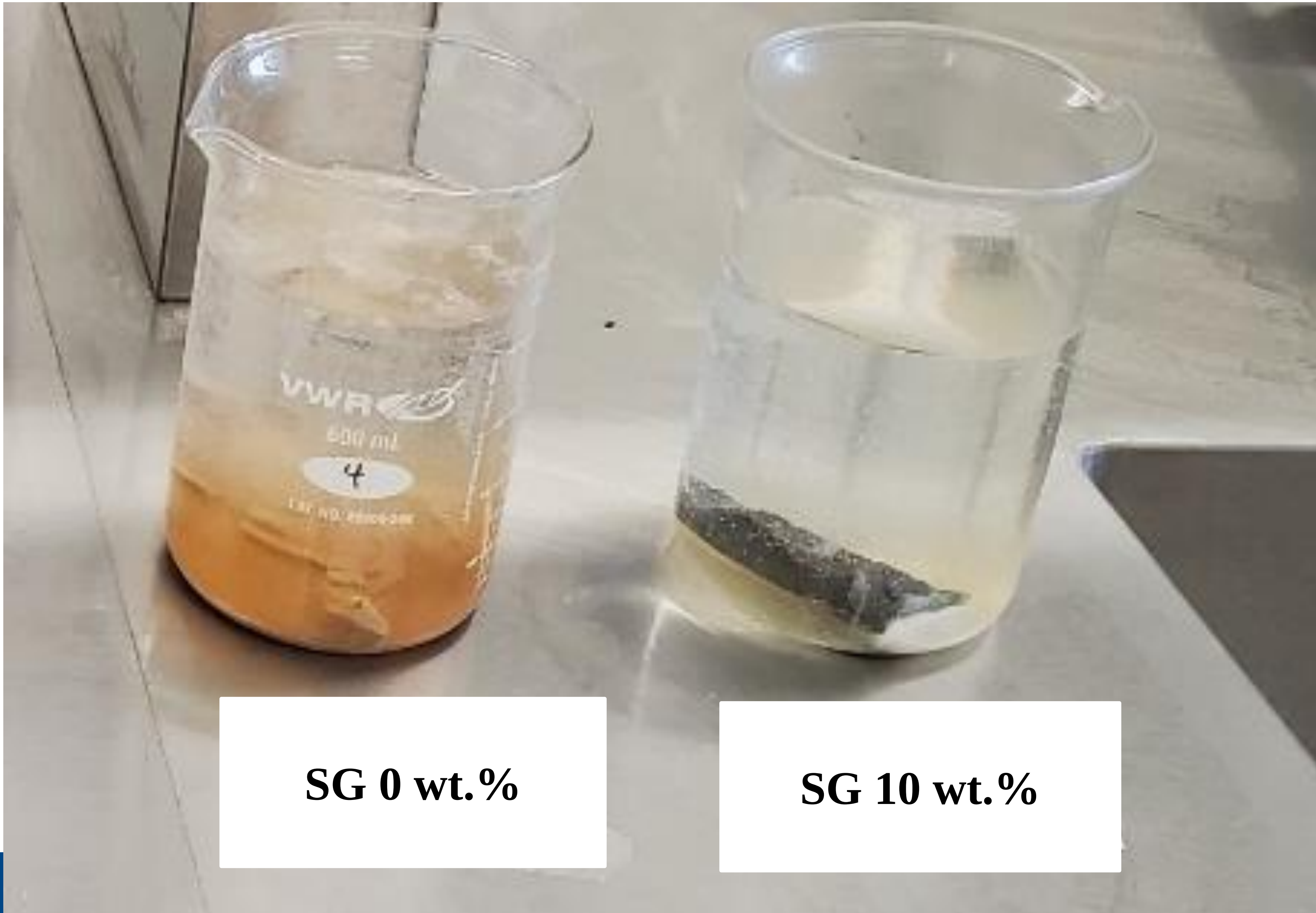


RESULTS AND DISCUSSION

The effect of NaOH molarity and SS/SH ratio

- ✓ **Increasing the NaOH molarity results in higher UCS and bulk density**
- ✓ **UCS and bulk density are increased by increasing the SS/SH ratio**

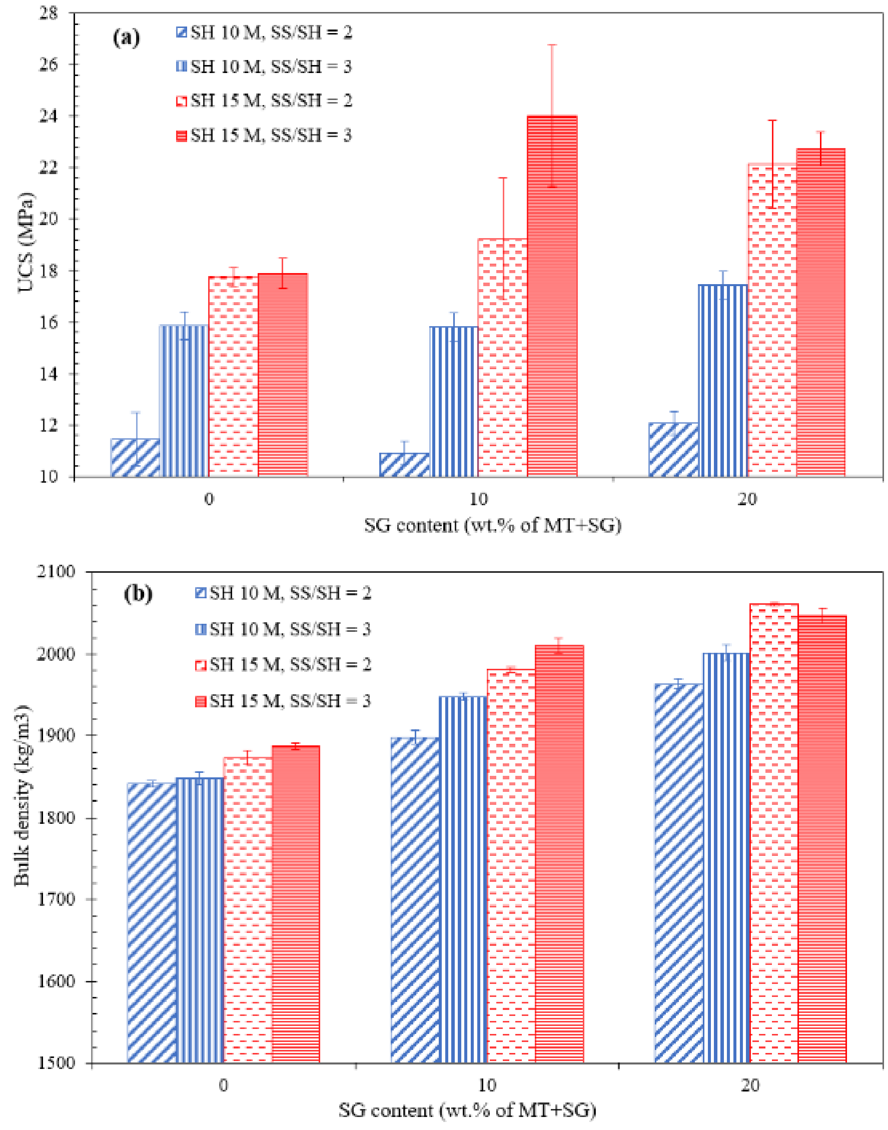



SG 0 wt.%
SG 10 wt.%

RESULTS AND DISCUSSION

The effect of SG content

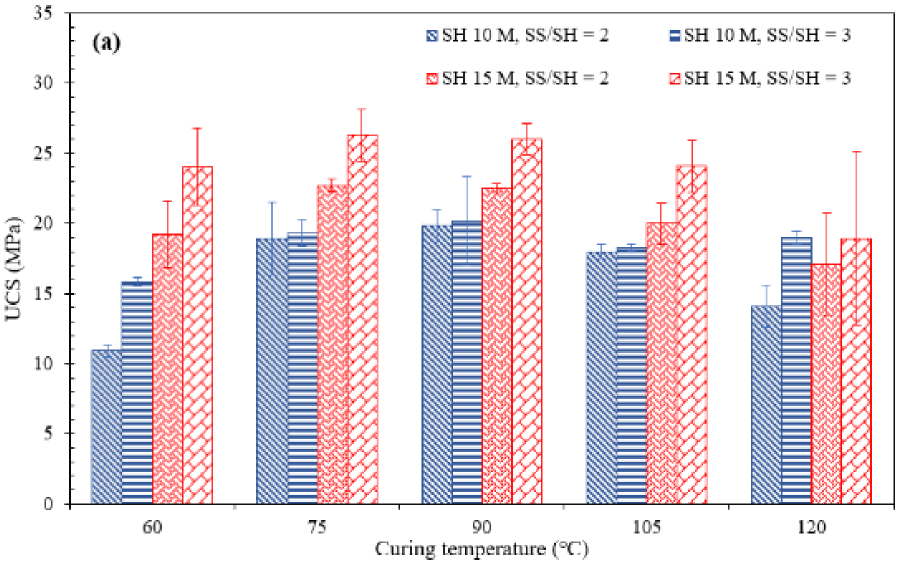
- ✓ **Higher SG content improves the geopolymerization and increases the bulk density**
- ✓ **10 wt.% SG is selected for the rest of study**

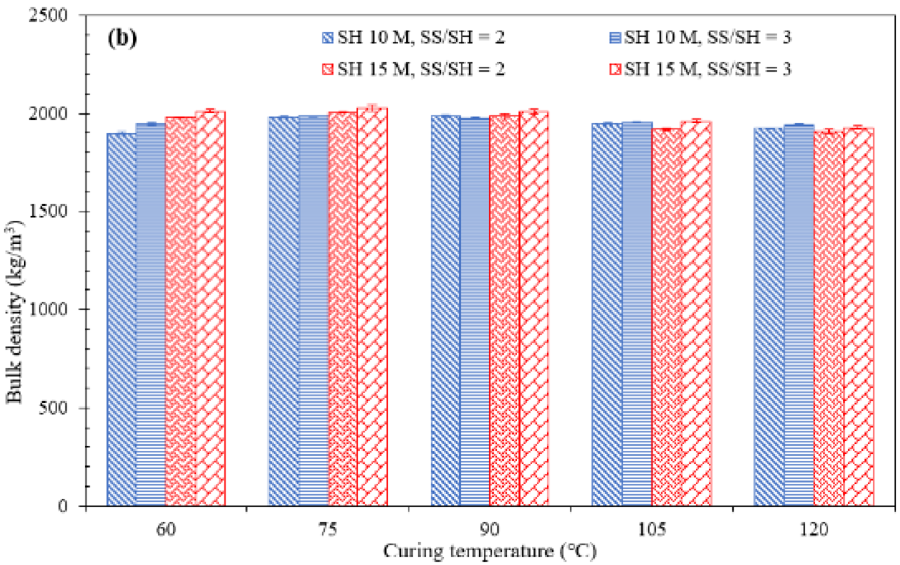


RESULTS AND DISCUSSION

The effect of curing temperature

- ✓ **UCS increases with curing temperature up to 90 ℃ and then decreases**
- ✓ **higher curing temperature accelerates the dissolution of silica and alumina and then the polycondensation**
- ✓ **Bulk density slightly increases with curing temperature up to 90 ℃ and then decreases**





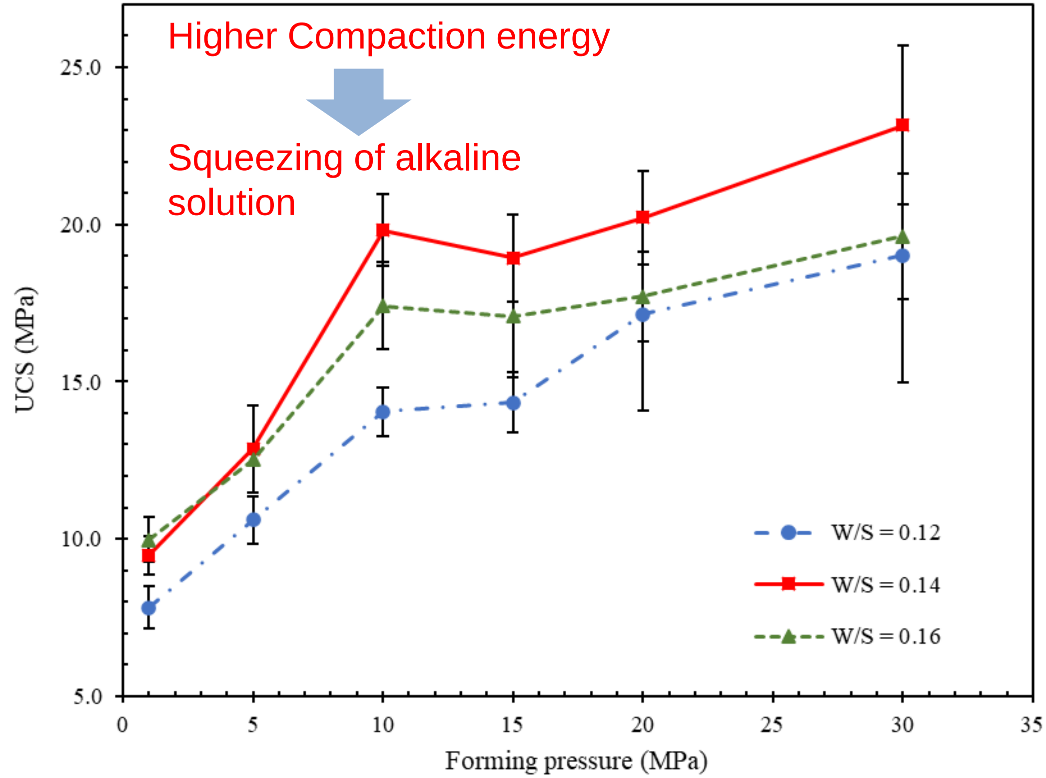
RESULTS AND DISCUSSION

The effect of water content and forming pressure

✓ **The effect of water content on the UCS is complex**

Lower W/S → Lower Na+ → Lower UCS

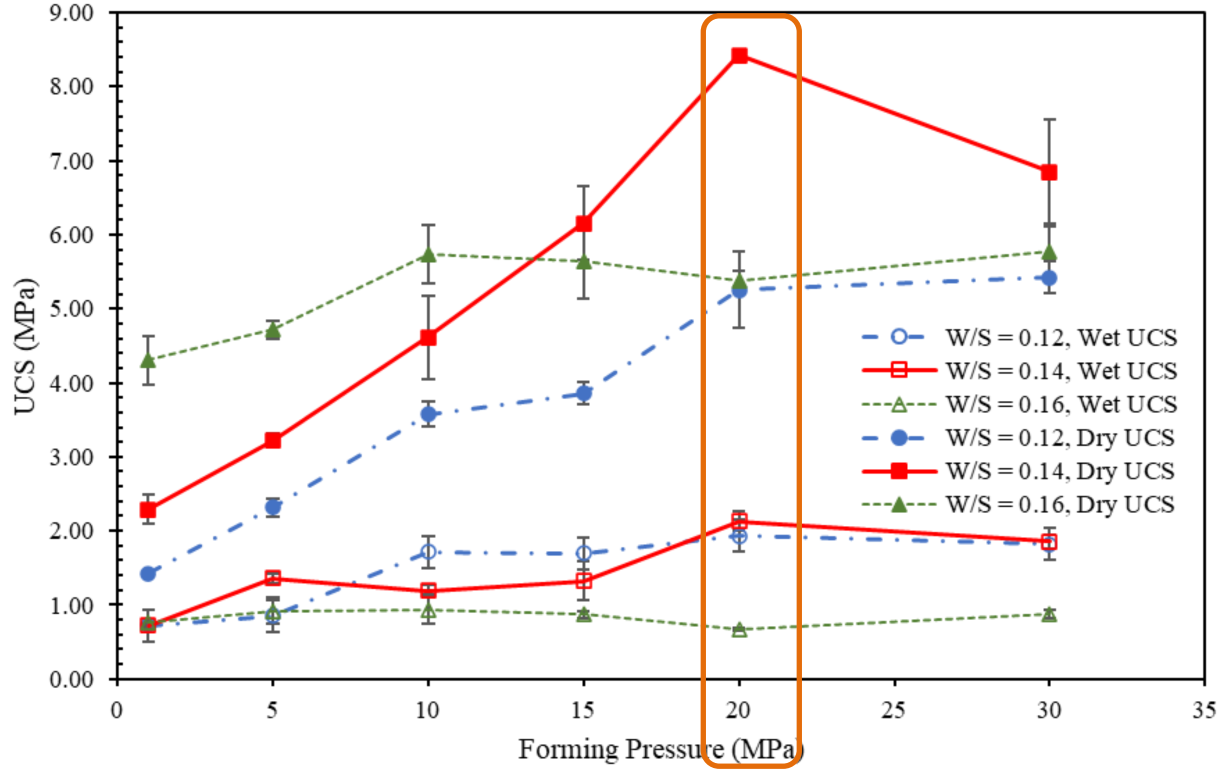
Higher W/S → Higher Na/Al & Na/Si → Higher UCS



RESULTS AND DISCUSSION

Water Absorption

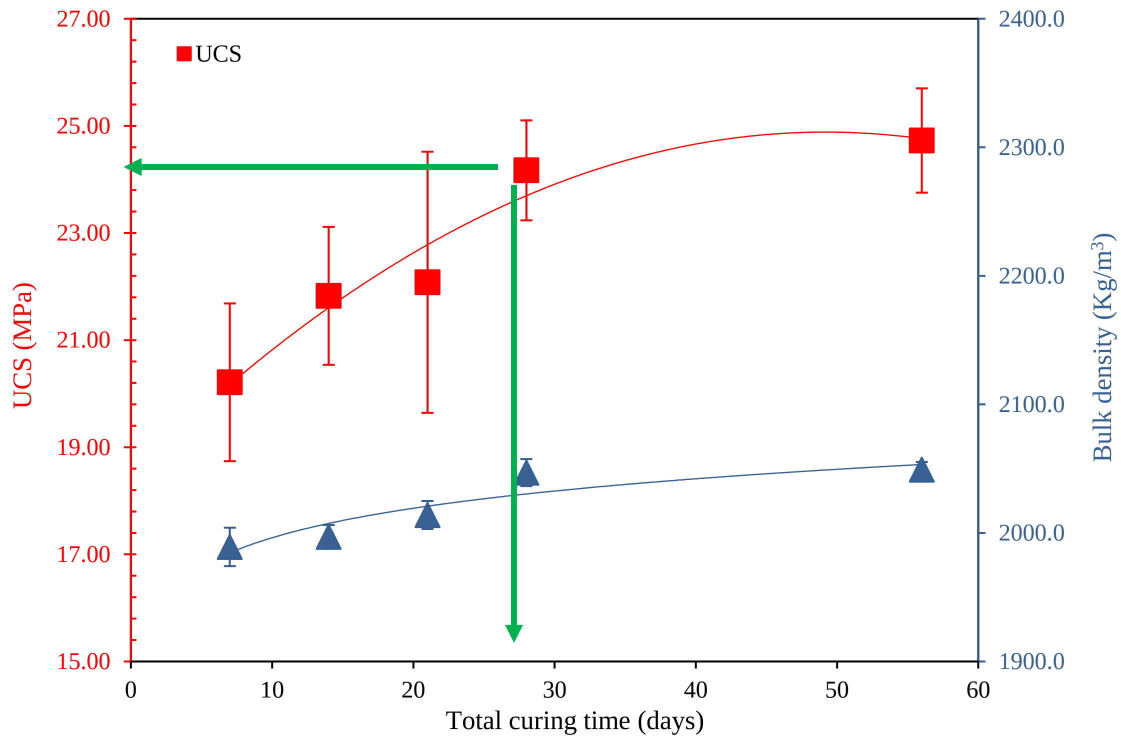
- ✓ **Water absorption is below 13.13%**
- ✓ **Increasing the forming pressure results in lower water absorption**
- ✓ **20 MPa was selected as the optimum forming pressure**

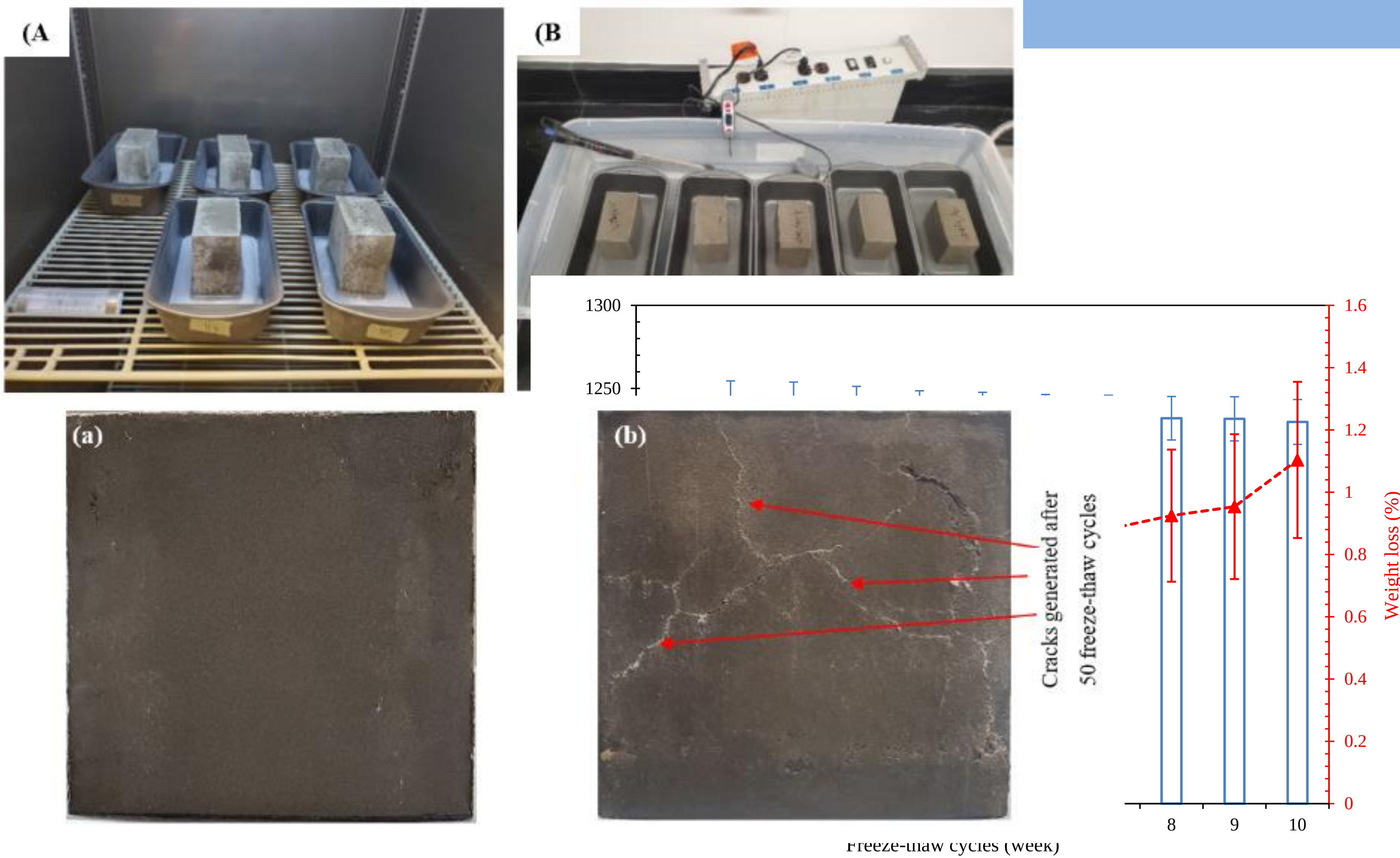


RESULTS AND DISCUSSION

The effect of curing time

- ✓ **UCS is increased significantly up to 28 days and then it is stabled**

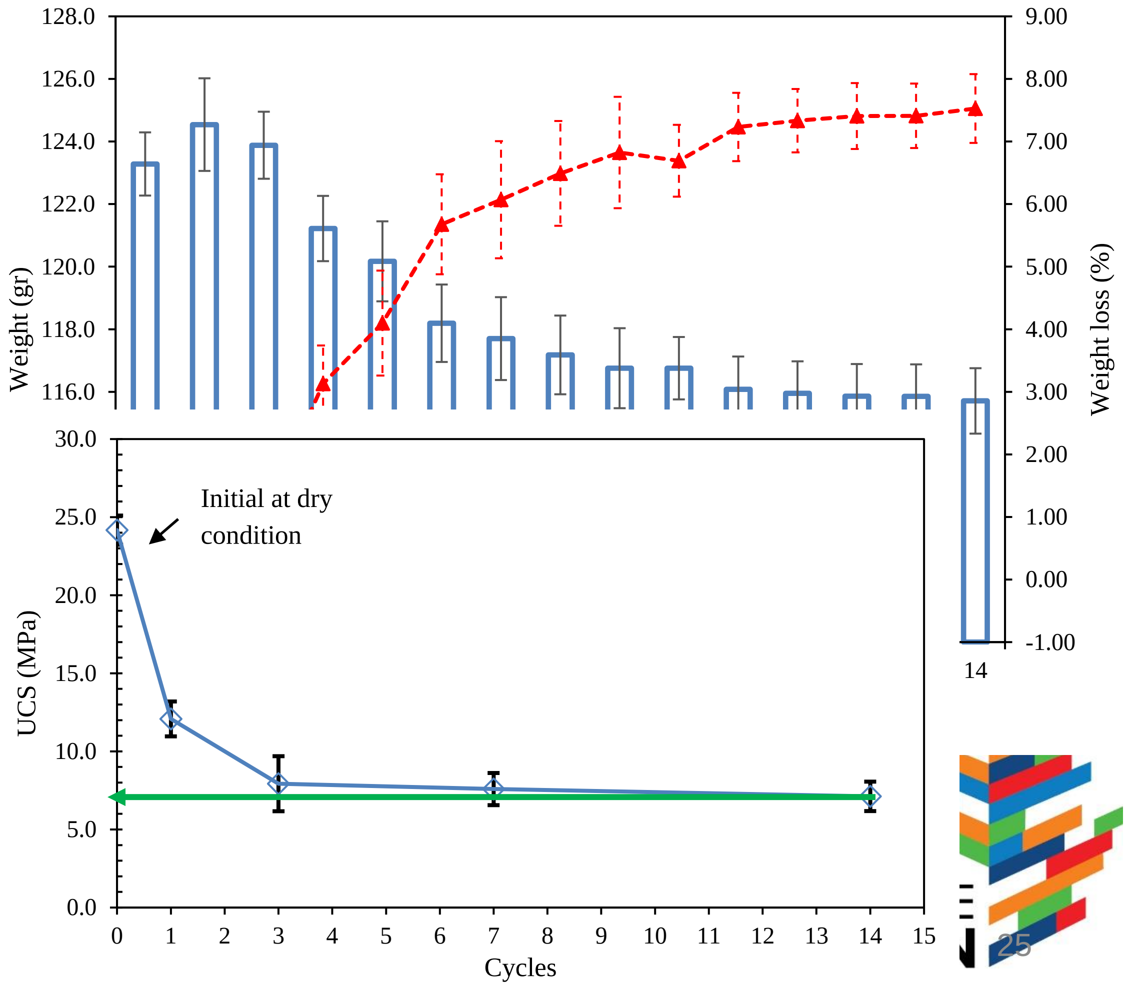


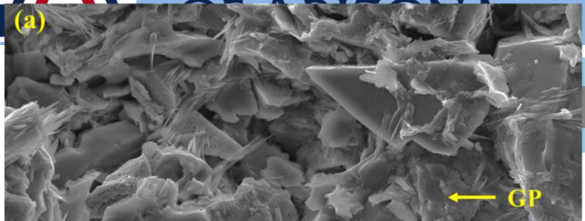

(A
(B
(a)
(b)
Cracks generated after
50 freeze-thaw cycles
1300
1250
8
9
10
Freeze-thaw cycles (week)
Weight loss (%)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0

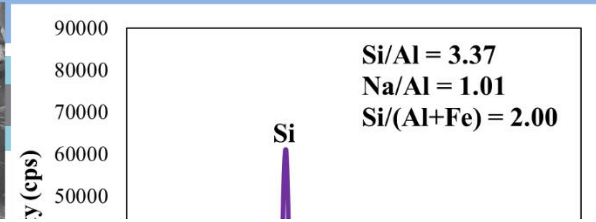
RESULTS AND DISCUSSION

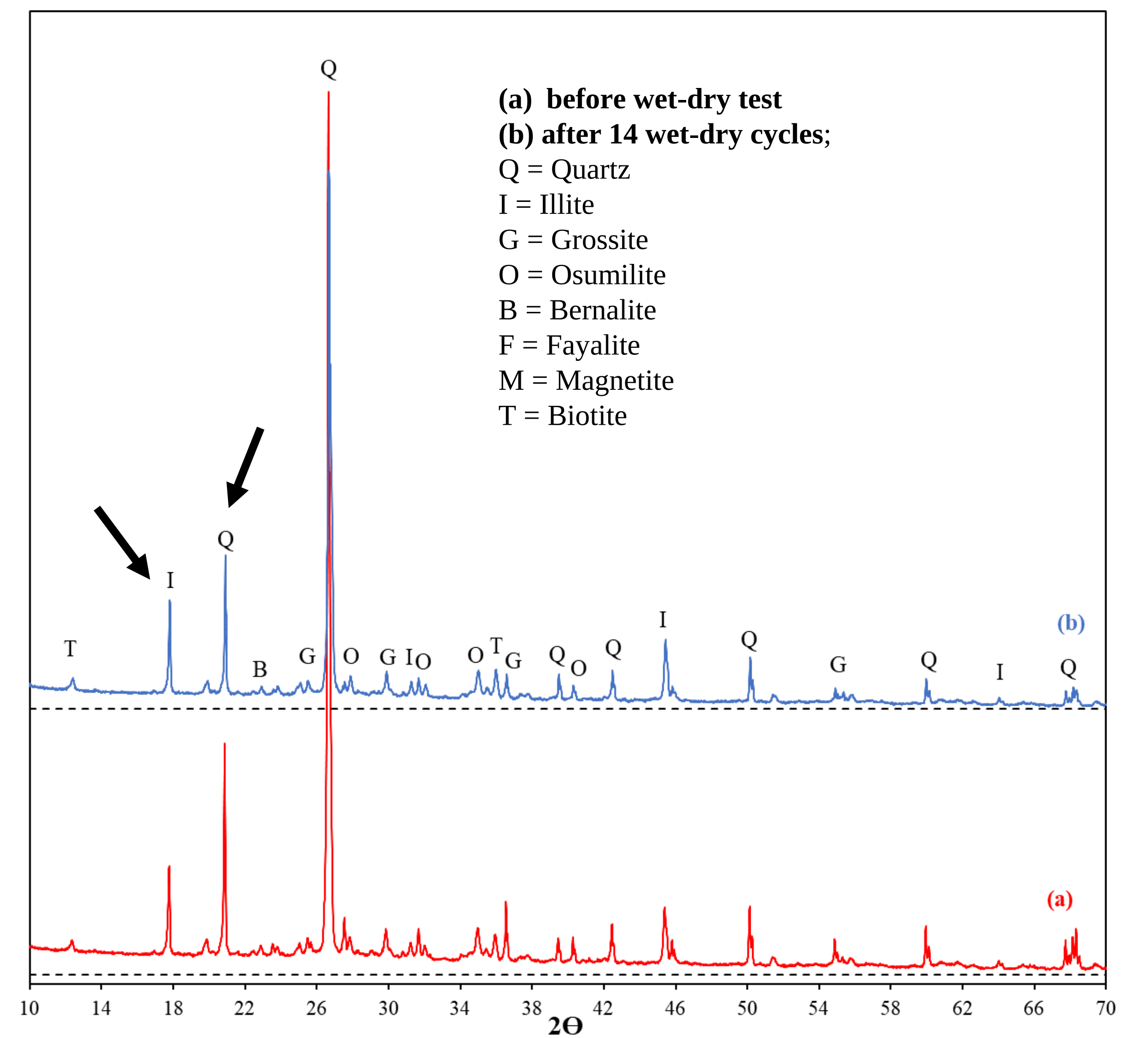
Wet-dry cycles

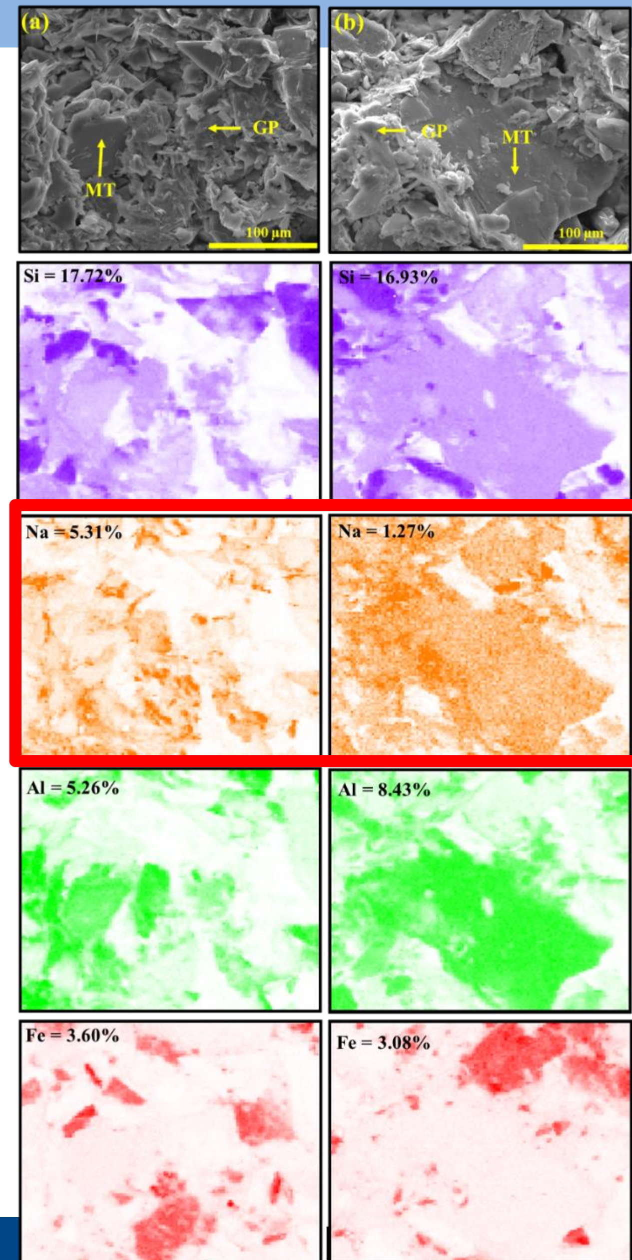
- ✓ **Total weight loss is 7.53%.**
- ✓ **The strength dropped from the initial 24.2 MPa to 7.12 MPa after 14 wet-dry cycles**




(a)
GP
(b)


90000
80000
70000
60000
50000
y (cps)
Si
Si/Al = 3.37
Na/Al = 1.01
Si/(Al+Fe) = 2.00


(a) before wet-dry test
(b) after 14 wet-dry cycles;
Q = Quartz
I = Illite
G = Grossite
O = Osumilite
B = Bernalite
F = Fayalite
M = Magnetite
T = Biotite
(b)
(a)
T I Q B G Q O G I O O T G Q O Q I Q G Q I Q
10 14 18 22 26 30 34 38 42 46 50 54 58 62 66 70
2Θ


(a)
(b)
GP
MT
100 μm
Si = 17.72%
Si = 16.93%
Na = 5.31%
Na = 1.27%
Al = 5.26%
Al = 8.43%
Fe = 3.60%
Fe = 3.08%

RESULTS AND DISCUSSION

Leaching test (TCLP)

	pH	Na	Mg	Al	K	Ca	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Mo	Cd	Pb
MT+SG powder	4	39.69	12.79	5.64	122.1	42.16	0.0	2.39	94.09	0.21	0.19	56.30	24.48	0.0	0.01	0.0	0.04	0.07
	7	213.4	5.18	0.03	226.1	33.99	0.0	0.88	0.02	0.03	0.02	0.22	0.61	0.0	0.05	0.46	0.0	0.0
Geopolymer specimen	4	1149	0.12	0.51	26.0	2.1	0.0	0.0	1.8	0.0	0.0	0.5	0.3	3.5	0.1	13.0	0.0	0.0
	7	1202	0.07	0.02	29.2	1.6	0.0	0.0	0.2	0.0	0.0	0.1	0.0	5.3	0.2	14.9	0.0	0.0
EPA limit		NA	NA	NA	NA	NA	5.0	NA	NA	NA	5.0	NA	NA	5.0	1.0	NA	1.0	5.0
DIN		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	2.0-5.0	2.0-5.0	NA	NA	NA	NA	NA
Greek		NA	NA	2.0-10.0	NA	NA	NA	1.0-2.0	NA	NA	0.2-0.5	0.25-0.5	2.5-5.0	NA	NA	NA	NA	NA

CONCLUSIONS

1 Using low-reactive copper MT and slag, geopolymer bricks were produced satisfying the ASTM requirements and at the same time stabilizing the hazardous elements.

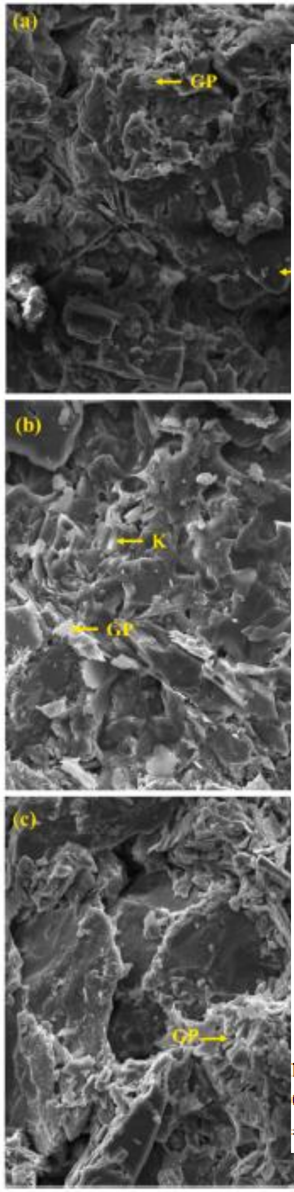
SPONSOR:

BHP

THANK YOU

RESULTS AND DISCUSSION

Oxides	Composition in percentage by weight	
	CC-MT	SG
SiO_2	61.2	32.9
Al_2O_3	24.6	2.43
K_2O	5.38	N/A
Fe_2O_3	4.35	37.50
Fe_3O_4	N/A	5.48
MgO	1.48	N/A
SO_3	1.23	1.56
TiO_2	0.84	N/A
P_2O_5	0.391	N/A
CaO	0.179	2.13
Cl	0.126	N/A
ZrO_2	0.055	N/A
SrO	0.038	N/A
Rb_2O	0.031	N/A
V_2O_5	0.030	N/A
CuO	0.030	N/A
MnO	0.025	N/A
MoO_3	0.025	N/A
Y_2O_3	0.009	N/A



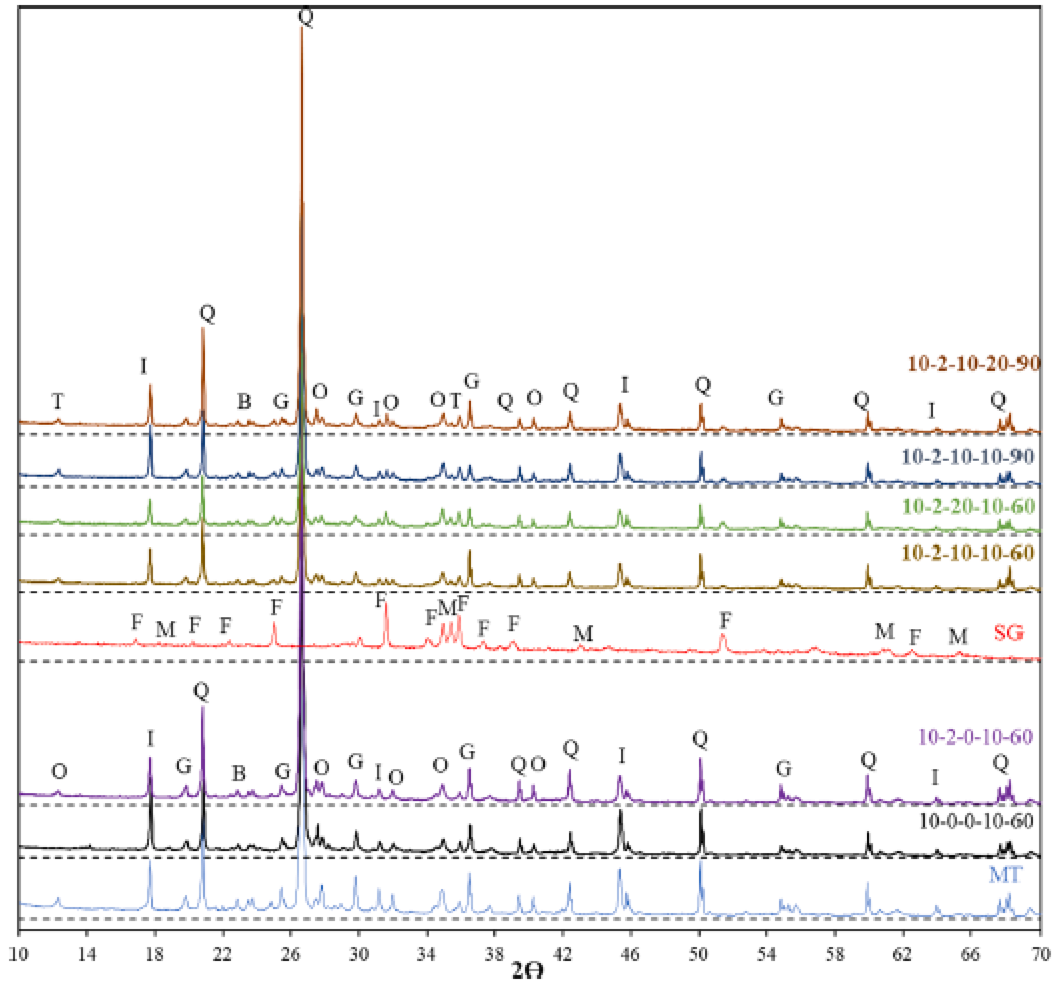


Fig. 19. XRD patterns of pure MT and SG powders and geopolymer specimens at different conditions: Q = Quartz (SiO_2), I = Illite ($(K, H_3O)Al_2Si_3AlO_{10}(OH)_2$), G = Grossite ($CaAl_4O_7$), O = Osumilite-Mg ($K_{0.9}(Fe_{0.02}Mg_{1.98})(Fe_{0.03}Al_{2.97})(Si_{10.13}Al_{1.87})O_{30}$), B = Bernalite ($Fe_3(OH)_3$), F = Fayalite ($Fe_2SiO_4$), M = Magnetite ($Fe_3O_4$), T = Biotite ($K(Mg,Fe)_3(AlSi_3O_{10})(F,OH)_2$). Specimen numbering: SH molarity-SS/SH ratio-SG content-forming pressure-curing temperature.

KeV

Fig. 15. SEM micrographs and EDX analysis results of geopolymer specimens at different SG contents and with the same W/S = 0.14, 10 MPa forming pressure, 10 M NaOH, SS/SH = 2, and curing temperature of 60 ℃ for 7 days: (a) 0 wt% SG; (b) 10 wt% SG; and (c) 20 wt% SG. GP = geopolymer gel, MT = mine tailings, and K = alkali-silica gel.