Decommissioning Sludge Waste Solidification in Geopolymer: An Optimization of Waste Loading and Physico-Mechanical Properties

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Introduction

- Sludge waste from Kori decommissioning represents a high-risk, chemically aggressive, and poorly characterized waste stream, requiring advanced material-based solutions for safe immobilization, volume reduction, and long-term disposal compliance.
- Decommissioning of **Kori Unit 1** will generate large mixed waste (**~600 drums decontamination**, **~84 drums sludge**) containing Co-60, Ni-59/63, and Fe-55.
- WAC restricts direct solidification of organic liquids—necessitating phase-separation pretreatment before immobilization

A separation and stabilization approach was used in this study, with a focus on
- **Minimize volume increase and maintain stability**
- **Improve disposal efficiency**

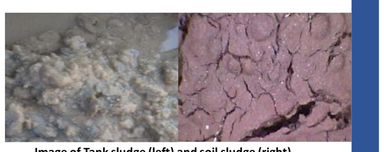


Image of Tank sludge (left) and soil sludge (right)

- Geopolymers (GPs) were selected as a sustainable, **low-carbon, low-calcium** alternative to conventional cementitious binders, offering high versatility, **scalability, and chemical durability**
- Sludge pre-treatment **involved chemical and thermal processes** to remove moisture and organic constituents, enabling effective downstream immobilization
- The separated and dried inorganic fractions of decontamination and sump sludge surrogates were immobilized using geopolymer binders up to **60 wt%.**
- The resulting waste forms were evaluated for mechanical integrity and durability performance

Materials and Methods

Chemical and thermal treatment of sludge to reduce water and organic contents

Decontamination wastewater (mM in 1L)

Leachates from pipe material			Oxidant		Reductant	Precipitant
$FeSO_4$	$CrK(SO_4)_2$	$NiSO_4$	$MnSO_4$	$NaNO_3$	$H_2C_2O_4$	$Ba(OH)_2$
1	0.5	0.5	1.67	2.5	20	100

Sludge after drying at room temperature

(wt. %)	BaC_2O_4	$BaSO_4$	$Mn(OH)_2$	$Ni(OH)_2$	$Cr(OH)_2$	$Fe(OH)_2$
Composition	79.2	15.1	2.6	0.8	0.8	1.6

Sludge after thermal decomposition at 500°C

(wt. %)	$BaCO_3$	$BaSO_4$	Fe_2O_3	Cr_2O_3	NiO	MnO_2
Composition	77.3	16.8	1.6	0.7	0.7	2.8

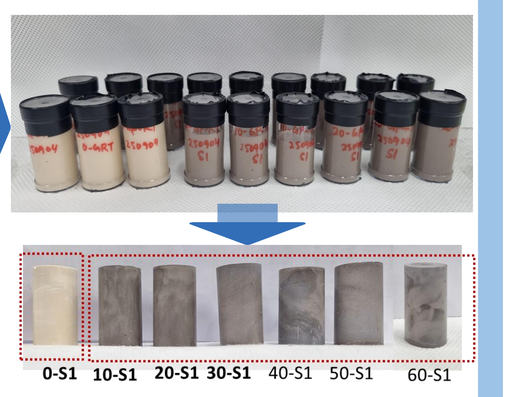
Reduction of organic content

TOC	C	BaC_2O_4
Initial (wt%)	4.84	45.43
After HT(wt%)	0.23	2.15

Sludge Type 1: Preparation of a surrogate sludge (S-1)

Cured for 28 days at room temperature (RT)

Sludge type/ coding	Loading, wt %
0-S1	0
10-S1	10
20-S1	20
30-S1	30
40-S1	40
50-S1	50
60-S1	60

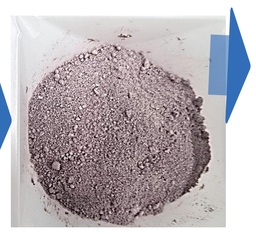


Sludge Type 2: Sump Sludge from Nuclear Facilities

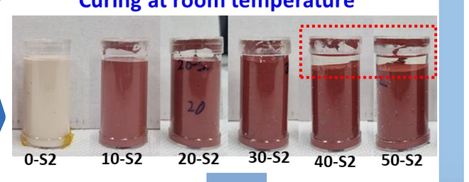
Compositions of sludges after heat-treatment

(wt. %)	SiO_2	Fe_2O_3	Al_2O_3	Na_2CO_3	K_2CO_3
Composition	56.84	17.59	15.57	5.44	4.51

Preparation of a surrogate Sludge (S-2)



Curing at room temperature



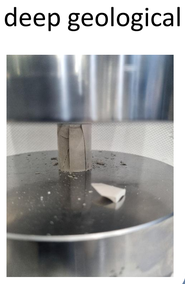
Sample deformed after curing

Compressive strength (ASTM C39/C39M)

The standard compressive strength test (ASTM C39/C39M-17b) was applied to ensure the robustness of the developed waste form during storage, handling, transportation, and disposal in a deep geological repository.

- Cylindrical samples with a length to diameter (L/D) ratio >1 were used in triplicate

Compressive Strength (MPa)=4×Max. Applied Force(N)/Area(πD^2)
Here, D is the diameter (mm)



Results and Discussions

Geopolymer waste form synthesis parameters were optimized by evaluating **compressive strength and bulk density** as a function of surrogate sludge waste loading.

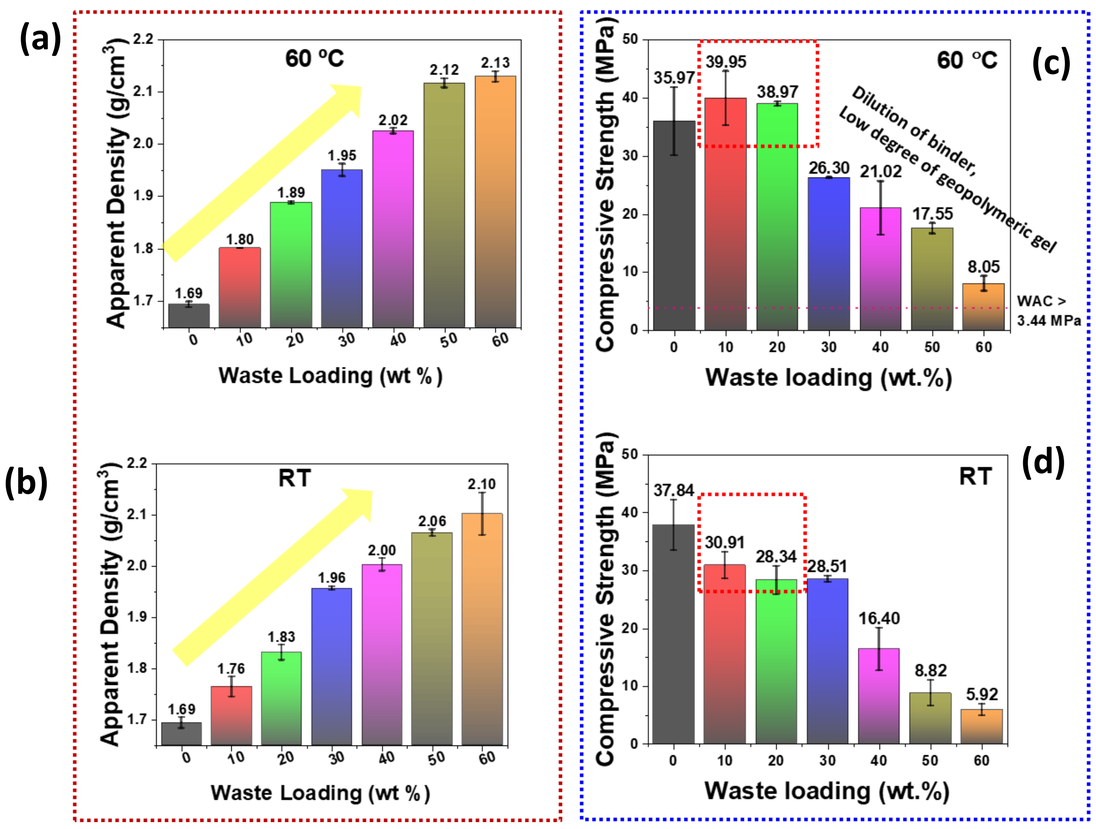


Fig. 1: Effect of S1 sludge loading on density and mechanical durability under RT and 60°C curing conditions

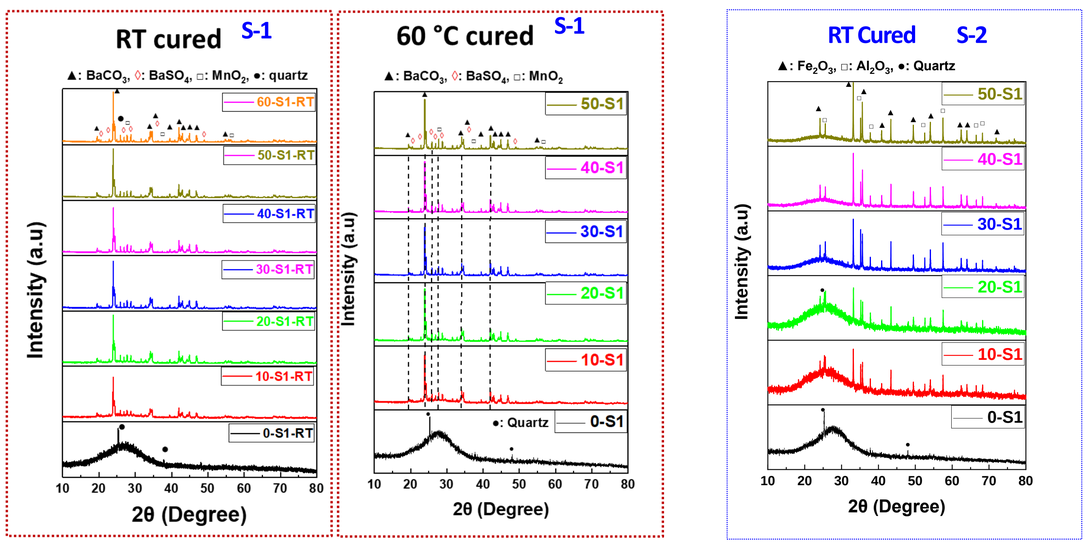


Fig. 2: XRD patterns of S1 (cured at RT and 60 °C) and S2 (RT) as a function of sludge loading

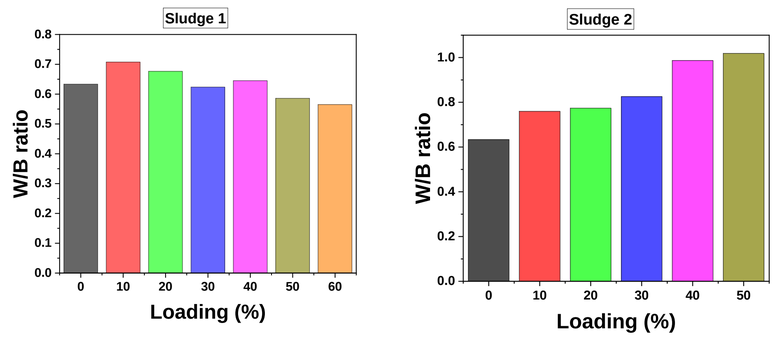


Fig. 3: Variation of water-to-binder (W/B) ratio with increasing S1 and S2 sludge loading

- Increasing S1/S2 content raises crystallinity due to $BaCO_3$, Fe_2O_3, and $BaSO_4$,. No new reaction phases are showing that the sludge is largely chemically inert
- Immobilization is dominated by physical encapsulation and pore filling. Matrix densification controls overall durability, not chemical bonding
- Apparent density increased with waste loading, possibly due to heavier elements loading and pore filling.
- Decrease in compressive strength beyond 30 wt% sludge is attributed to binder dilution, increased unreactive/weak phases, and higher water demand

Conclusions

- **Decontamination sludge (S1)** demonstrated **successful immobilization in geopolymer matrices**, achieving **excellent mechanical strength and stable solidification behavior at room temperature and 60 wt%.**
- **Sump sludge (S2)** exhibited **poor curing performance**, primarily because of high **water-to-binder (w/b > 1) ratio** due to high amount of silica.
- **XRD analysis** confirmed that sludge constituents predominantly remain **chemically inert** as **crystalline phases within the geopolymer matrix.**
- **This work demonstrates an effective pathway to convert sludge radioactive wastes into a durable and disposal-ready waste form**

Acknowledgements

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