A sustainable shift in road construction: the potential of alkali-activated binders and waste glass reuse

by: Sara Bayandor
sara.bayandor@autuni.ac.nz
PhD Candidate at AUT

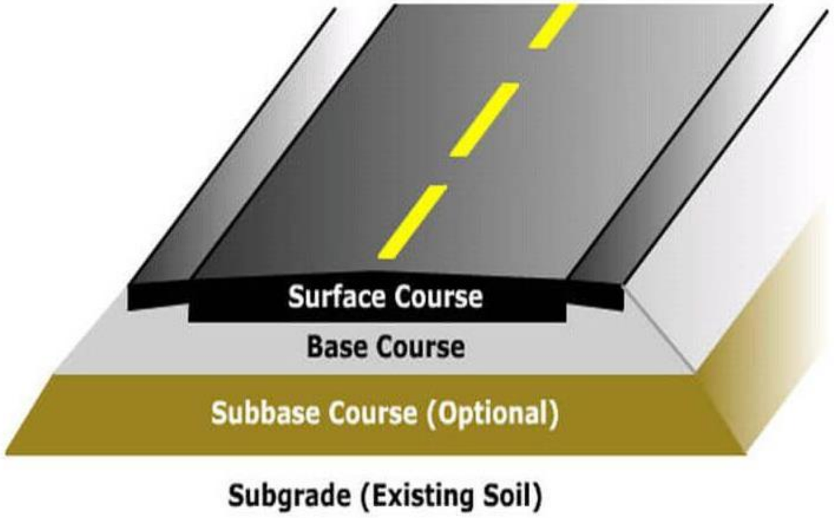
Supervisors: Dr. Roohollah Kalatehjari
Dr. Afshin Asadi

Overview:

- Do we need an alternative for cement and lime?
- What are Alkali Activated Materials?
- What is the history of employing Alkali Activated Materials?
- What are the required (local) precursor/raw materials?
- Can we use Waste Glass in Alkali Activated Materials?
- What are the local benefits of such research?
- What are the potential studies in this field?

Introduction:

- Sustainability, infrastructure development, waste management, and soil stabilisation.
- A typical pavement: the pavement, earthwork, the subgrade layer.
- Soil stabilisation in soft or loose soils, such as expansive clays or loose silty or sandy soils.
- Conventional soil stabilisation methods typically use additives such as **cement** and **lime** mixed with soil.



Conventional additives:

- Cement has a massive carbon footprint, contributing to ≈ 8 % of the world's carbon dioxide (CO_2) emissions [1, 2]

- Growth of demand for cement is expected with the population increase, especially in developing countries.

- Extract, Crush raw materials (mainly limestone and clay)

- Heating the raw material (1,300 °C or higher)

- Calcination process by heating limestone

- $CaCO_3$ (1 kg) $\longrightarrow$ Cao (0.56 kg)+ CO_2 (0.44 kg) [1]

- Lime raw material can be burned at lower temperatures – 900~1,000 °C

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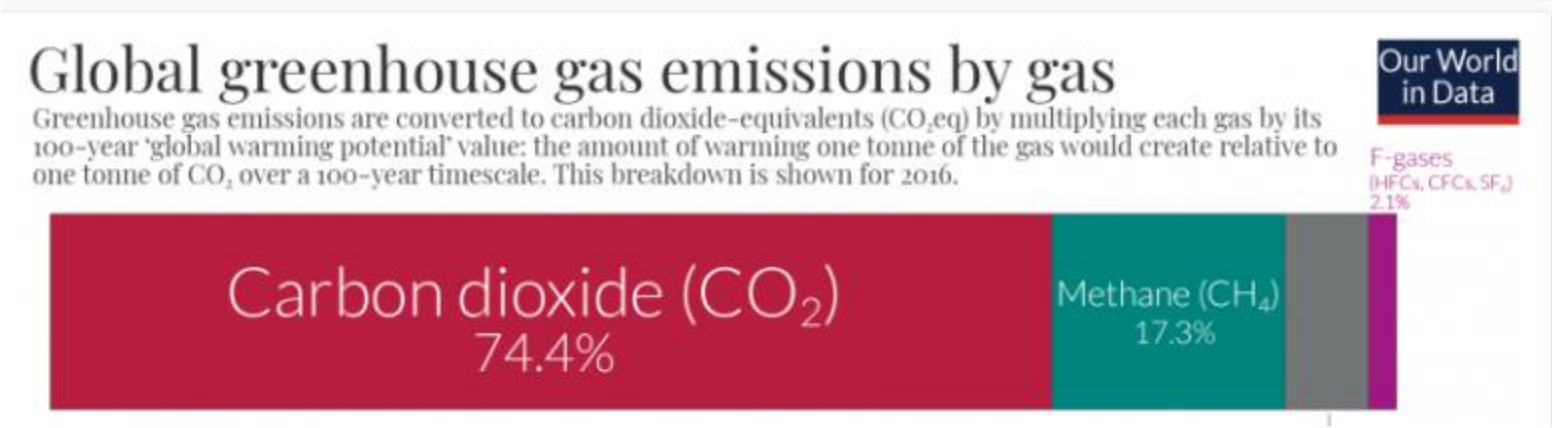
1. Provis, J. L., & Van Deventer, J. S. (Eds.). (2013). *Alkali activated materials: state-of-the-art report, RILEM TC 224-AAM* (Vol. 13). Springer Science & Business Media.
2. Andrew, R.M., 2018. Global CO2 emissions from cement production. Earth Syst. Sci. Data 10, 195. https://doi.org/10.5194/essd-10-195-2018.

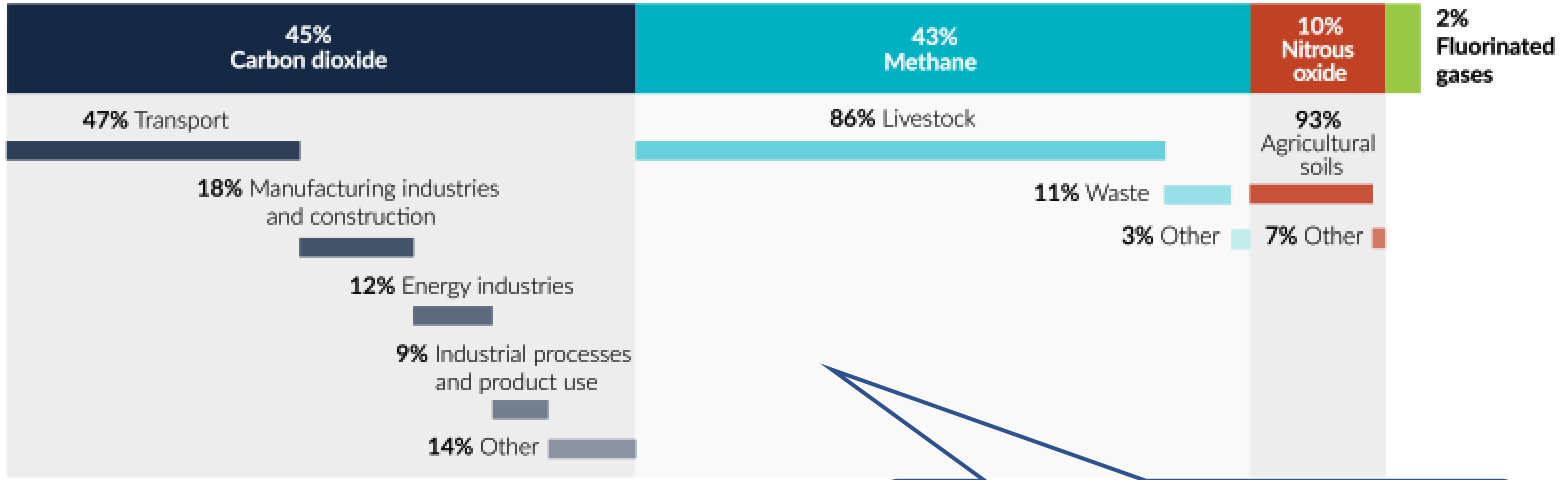
Carbon dioxide emission in World (2016), NZ (2018)



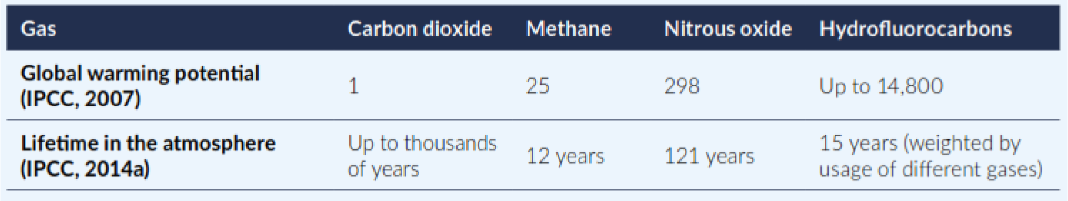
Global greenhouse gas emissions by gas

Greenhouse gas emissions are converted to carbon dioxide-equivalents (CO_2eq) by multiplying each gas by its 100-year 'global warming potential' value: the amount of warming one tonne of the gas would create relative to one tonne of CO_2 over a 100-year timescale. This breakdown is shown for 2016.

- New Zealand's average annual temperature has risen by 1.13 °C from 1909 to 2019.
- New Zealand's net emissions have increased by 57% from 1990 to 2018.



"Our atmosphere and climate 2020"
https://ourworldindata.org/

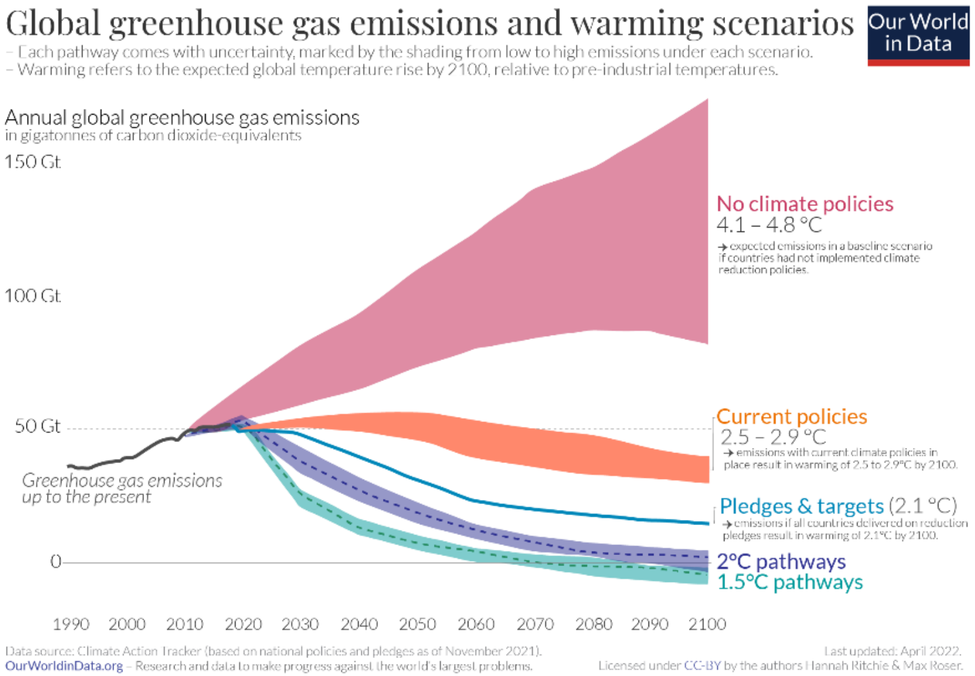


Gas	Carbon dioxide	Methane	Nitrous oxide	Hydrofluorocarbons
Global warming potential (IPCC, 2007)	1	25	298	Up to 14,800
Lifetime in the atmosphere (IPCC, 2014a)	Up to thousands of years	12 years	121 years	15 years (weighted by usage of different gases)

Limiting GHG emissions:

- UNFCCC
- Kyoto Protocol

The Paris agreement
2015-2016
190 parties
2°C-1.5°C
Net-Zero by 2050
Transparent Goals
Transparent Reports
All parties are under commitment.




Top 10 CO_2-emitting countries in the world

1. China — 11680.42
2. United States — 4535.30
3. India — 2411.73
4. Russia — 1674.23
5. Japan — 1061.77
6. Iran — 690.24
7. Germany — 636.88
8. South Korea — 621.47
9. Saudi Arabia — 588.81
10. Indonesia — 568.27

GHG emission (2020)
total CO_2(mt)
NZ:72

- New Zealand Nationally Determined Contribution (NDC1) sets a headline target of a **50% reduction** of net emissions below the gross 2005 level by 2030.
- Net zero emissions of all greenhouse gases other than biogenic methane by 2050.

Alkali-Activated Materials (AAMs):

- Activation of raw precursor with alkali source

- Precursor materials: → Industrial Waste (blast furnace slags, Fly ash, metakaolin,…)
  → Natural Materials (Pozzolan, Clay)

- Common activators: KOH, NaOH, Na_2Sio_3 , …

(accelerate the reaction process and induces the strong formation)

- 40~80% CO_2 saving [1, 2]
  mainly by avoiding carbonate precursors such as limestone ($CaCO_3$), and fossil fuel-fried kiln

- The cost of AAC vary from 19% lower to 48% higher compared with PC concrete [3].

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2. Davidovits, Joseph. "False values on CO2 emission for geopolymer cement/concrete published in scientific papers." *Technical paper* 24 (2015): 1-9.
3. Vinai, R., Soutsos, M., 2019. Production of sodium silicate powder from waste glass cullet for alkali activation of alternative binders. Cem. Concr. Res. 116, 45–56.

History:

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-Purdon AO. 1940. The action of alkalis on blast-furnace slag. *J. Soc. Chem. Ind. Trans. Commun. 59:191–*
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- Buchwald A, Vanooteghem M, Gruyaert E, Hilbig H, De Belie N. 2014. Purdocement: application of alkali-activated slag cement in Belgium in the 1950s. *Mater. Struct. In press; doi:10.1617/s11527-0130200-8*

- 1870s in France and Germany: Metallurgical slags, Blast Furnace Slag (BFS)
- 1930s in the United States: Fly Ash as a cementing binder
- 1940 in Belgium: the first extensive laboratory study on cement consisting of slag and alkalis
- 1950s in the former Soviet Union: the binders using low-Calcium or calcium-free aluminosilicate precursors activated by alkaline solutions were developed, known as "Soil cement" binders and "soil silicates" binders.
- 1970s in France: Alkali-activated binders based on metakaolin were developed. Fire-resistant, inorganic resin "geopolymer" similar to organic thermoset resins.
- 1980s in Northern Europe: alkali-activated slag concrete or "F-concrete" were commercialised.
- In China: Using metallurgical slags, high-strength concrete (>80 MPa)

Real-World Applications of Alkali-Activated Technology:

Figure 1. Residential building, alkali hydroxide-activated BFS, Mariupol, Ukraine, 1960 (P. V. Krivenko, 1994)

Figure 2. 24-storey building, alkali-activated BFS concrete, Lipetsk, Russia, 1986~1994 (P. V. Krivenko, 1994)

Figure 3. Comparison of Ordinary concrete cement road (right side) and cast-in-situ alkali-activated slag concrete (left) in Ternopil, Ukraine concrete (P. Krivenko, 2002)

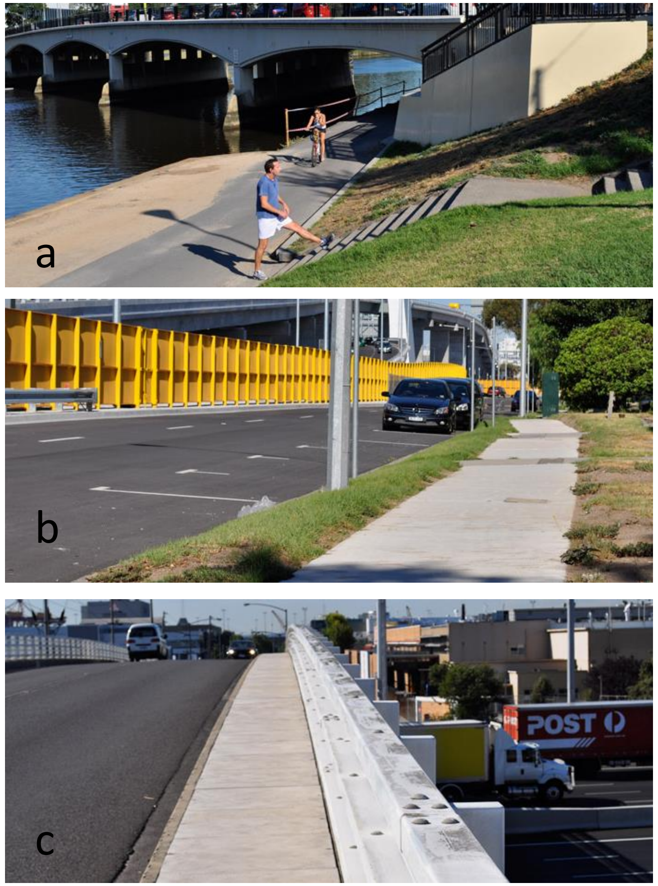


Figure 4. Examples of E-Crete in Australia: (a) in-situ retaining wall, (b) freeway, (c) precast bridge panels, Zeobond Pty. Ltd., (http://www.zeobond.com/).

AAM Binders

High Ca Binders

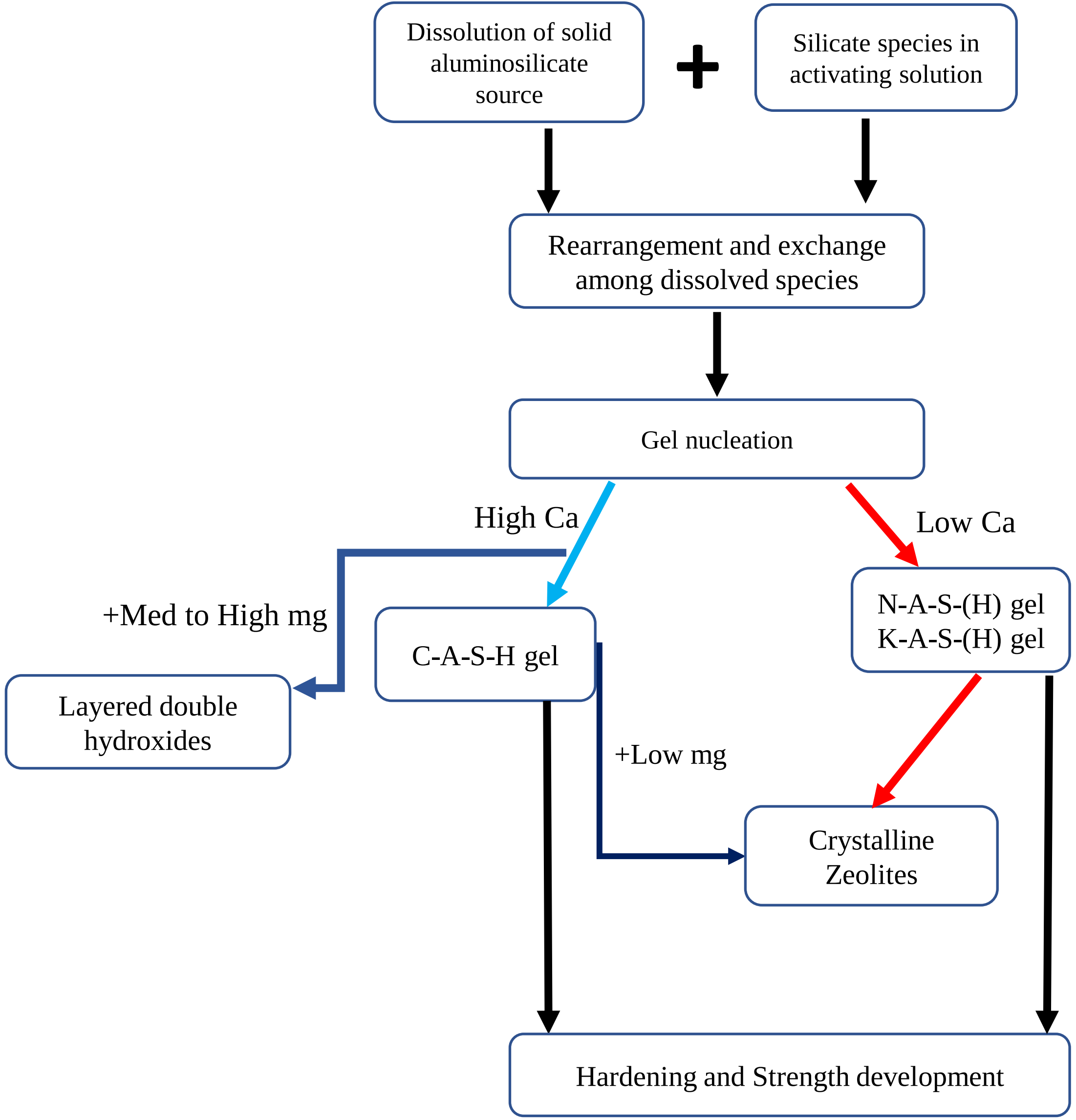
- Ca/(Si+Al)=1
- Slag
- High Ca Fly Ash
- Less permeability

Blended Systems

- Medium Ca

Low Ca Binders /Geopolymers

- Metakaoline
- Clay
- Low Ca Fly Ash



Dissolution of solid aluminosilicate source

+

Silicate species in activating solution

Rearrangement and exchange among dissolved species

Gel nucleation

High Ca

Low Ca

+Med to High mg

Layered double hydroxides

C-A-S-H gel

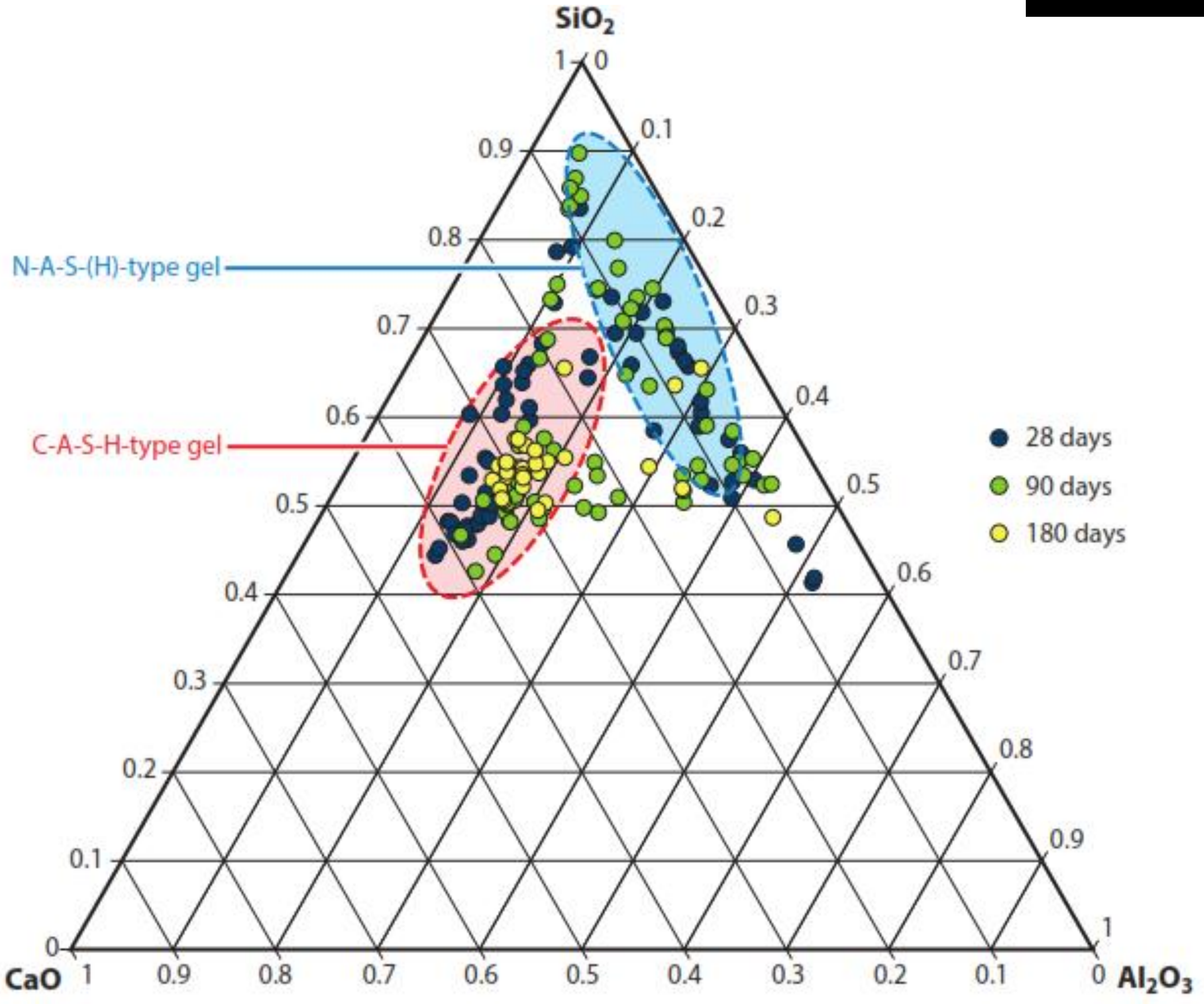
N-A-S-(H) gel
K-A-S-(H) gel

+Low mg

Crystalline Zeolites

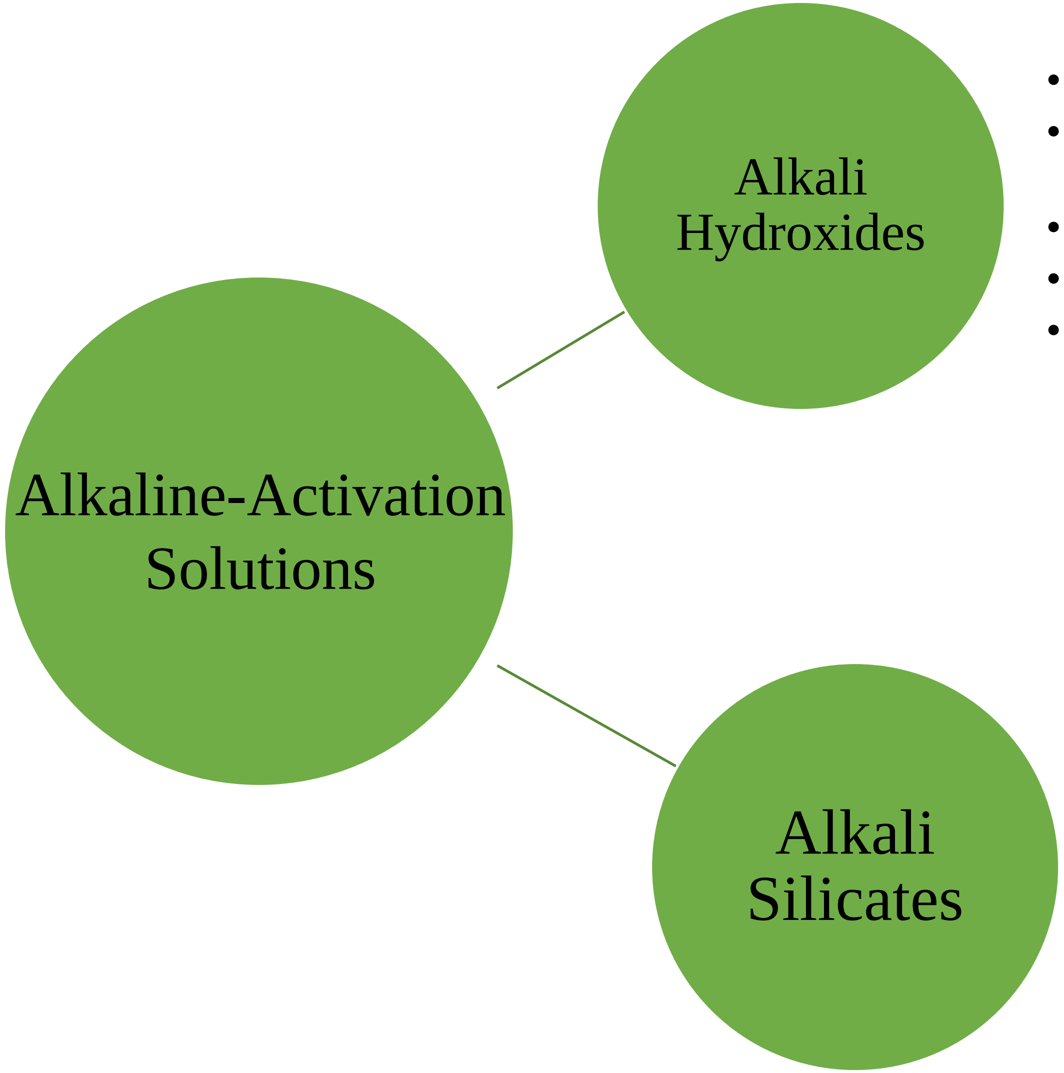
Hardening and Strength development

Elemental compositions measured for gel regions:



- Provis, John L., and Susan A. Bernal. "Geopolymers and related alkali-activated materials." *Annual Review of Materials Research* 44 (2014): 299-327.

Alkali-Activated Materials (AAMs) Classifications:



Alkaline-Activation Solutions

Alkali Hydroxides

- NaOH, KOH, …
- Low-Ca precursor, corrosive, health & safety consideration
- Thermal curing (Fly Ash)
- Higher permeability
- More favorable workability

Alkali Silicates

- Carbonate salts, Silika
- Lower PH, Irritants not corrosive
- Unfavorable high viscosity
- Potassium silicate solutions show a much lower viscosity than do sodium silicates

Waste glass:

- In most countries, waste glass cannot be fully recycled or reused and sent to landfills.
- In China, about 53.5% of the total waste glass (about 1070 million tons) was recycled in 2017.
- In the United States, approximately 11.6 million tons of urban waste glasses was generated in 2012 and only 28% was recycled.
- In Spain, over 700,000 tons of glass is consumed annually and approximately 70% of the total is recycled.
- In New Zealand, at least 27% of waste glass (almost 60,000 tons) was landfilled in 2016.

-MOFCOM (Minister of Commerce of the People's Republic of China), 2018. China Renewable Resources Recycling Industry Development Report (2018).
-Escalante-Garcia, J.I., 2015. Overview of potential of urban waste glass as a cementitious material in alternative chemically activated binders. J. Chin. Ceram. Soc. 43 (10),1441–1448.
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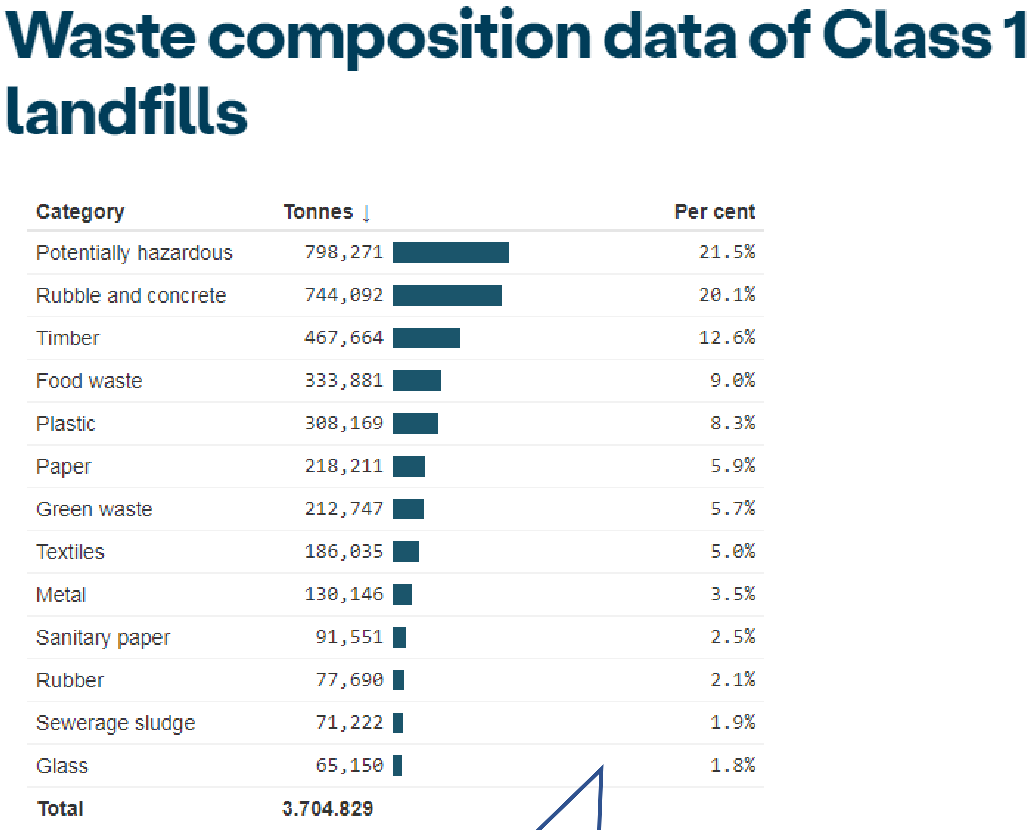
Chemical process and hydration products. Constr. Build. Mater. 139, 342–354.
-Cann, G. (2017). Isolation, and apathy among reasons 60,000T of recyclable glass goes to landfill. Retrieved fromhttps://www.stuff.co.nz/environment/90757924/isolation-apathy-among-reasons-60000t-of-recyclable-glass-goes-to-landfill.

Waste glass:

- These glass wastes have been identified as a potential source of silicate, this being 70–75% of amorphous silica. The reuse of waste glasses as aggregate, precursors, and activators in the preparation of alkali-activated binder seems a viable path to efficiently utilising this solid waste and reducing the cost of the binder (Liu et al., 2019).

- New Zealand provides an ample amount of volcanic ash as a natural pozzolan. The waste glass powder in adjunct with this natural pozzolan is used in the proposed innovation to produce a sustainable method for stabilising local soft soil in road construction.



Waste composition data of Class 1 landfills

Category	Tonnes ↓	Per cent
Potentially hazardous	798,271	21.5%
Rubble and concrete	744,092	20.1%
Timber	467,664	12.6%
Food waste	333,881	9.0%
Plastic	308,169	8.3%
Paper	218,211	5.9%
Green waste	212,747	5.7%
Textiles	186,035	5.0%
Metal	130,146	3.5%
Sanitary paper	91,551	2.5%
Rubber	77,690	2.1%
Sewerage sludge	71,222	1.9%
Glass	65,150	1.8%
Total	**3.704.829**	

https://environment.govt.nz/facts-and science/waste/estimates-of-waste-generated/#types-of-waste-going-to-class-1-landfills

Utilization of waste glass:

Waste Glass

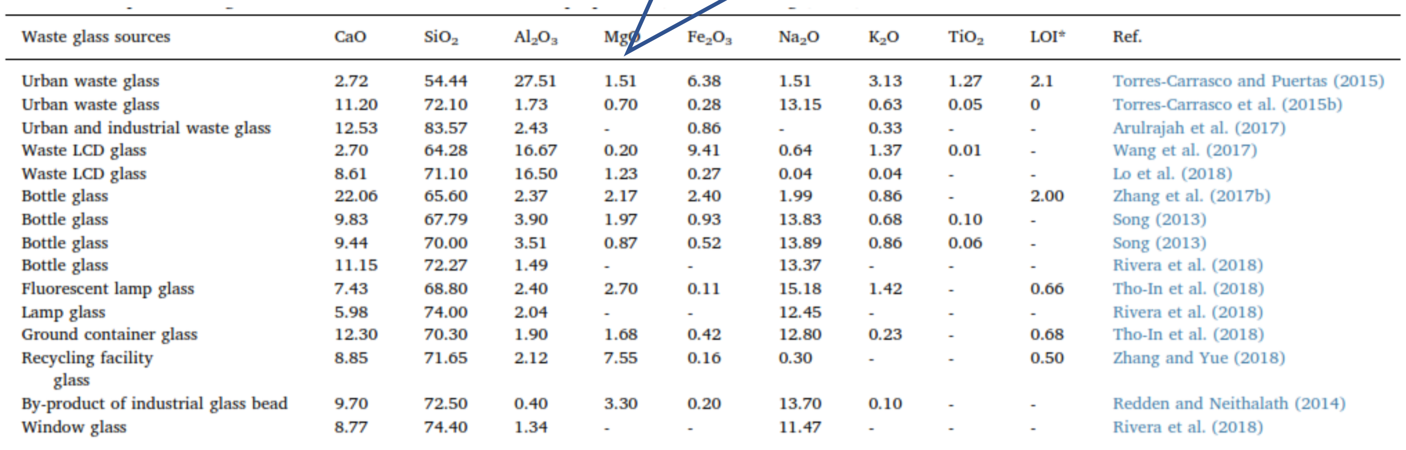
- **Aggregate**
  - Workability
  - Thermal connectivity
  - Capacity against Sulfate attack
  - Reduce the Strength
  - Enhance the Flexural Strength
- **Precursors**
  - Strength ($Na2O$)
  - Calcium Aluminate Cement (CAC)
  - Efflorescence in humid regions (FA, CAC, Heating in curing process)
- **Activator**
  - Fusion method (550 °C)
  - Hydrothermal method (80 °C-100°C)
  - Thermochemical method (150-450°C)

Conclusion:

- While cement and lime stabilisation have successfully improved the performance of soils in road construction projects, such additives present some limitations.
  - high-energy consumption
  - CO_2 emissions.
- The application of alkali-activation technology in road construction projects is a rapidly emerging field that aligns with the pursuit of sustainable and eco-efficient construction practices.
- The durability, low energy consumption, and reduced CO_2 emissions associated with AAMs make them an attractive alternative in road construction.
- Incorporating waste glass as a precursor in producing AABs for road construction projects:
  - reduces the quantities of waste glass that would otherwise end up in landfills,
  - diminishes the dependency on extracting fresh raw materials for road construction,
  - preserving natural resources
  - reducing the environmental footprint associated with mining and extraction processes.

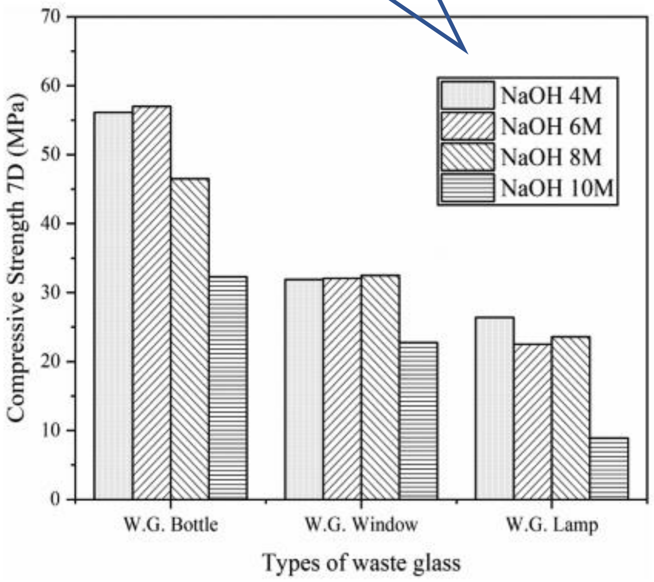
Challenges and Future Studies:

Chemical Composition

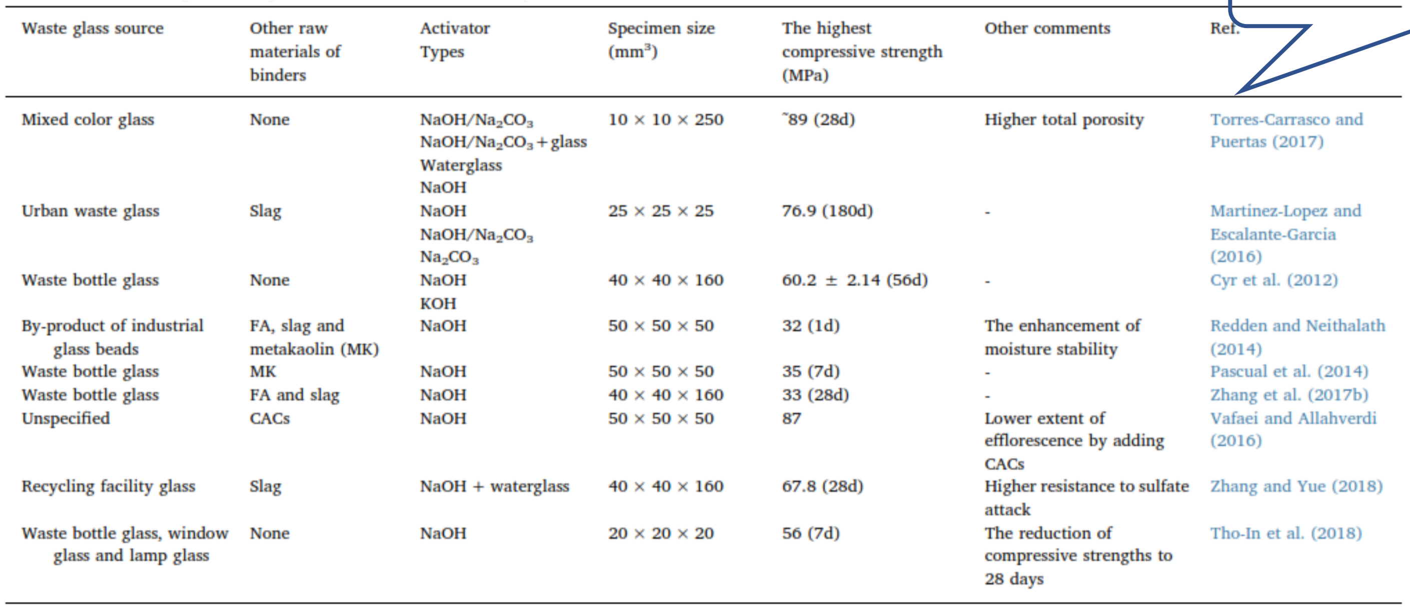


Waste glass sources	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	Na_2O	K_2O	TiO_2	LOI*	Ref.
Urban waste glass	2.72	54.44	27.51	1.51	6.38	1.51	3.13	1.27	2.1	Torres-Carrasco and Puertas (2015)
Urban waste glass	11.20	72.10	1.73	0.70	0.28	13.15	0.63	0.05	0	Torres-Carrasco et al. (2015b)
Urban and industrial waste glass	12.53	83.57	2.43	-	0.86	-	0.33	-	-	Arulrajah et al. (2017)
Waste LCD glass	2.70	64.28	16.67	0.20	9.41	0.64	1.37	0.01	-	Wang et al. (2017)
Waste LCD glass	8.61	71.10	16.50	1.23	0.27	0.04	0.04	-	-	Lo et al. (2018)
Bottle glass	22.06	65.60	2.37	2.17	2.40	1.99	0.86	-	2.00	Zhang et al. (2017b)
Bottle glass	9.83	67.79	3.90	1.97	0.93	13.83	0.68	0.10	-	Song (2013)
Bottle glass	9.44	70.00	3.51	0.87	0.52	13.89	0.86	0.06	-	Song (2013)
Bottle glass	11.15	72.27	1.49	-	-	13.37	-	-	-	Rivera et al. (2018)
Fluorescent lamp glass	7.43	68.80	2.40	2.70	0.11	15.18	1.42	-	0.66	Tho-In et al. (2018)
Lamp glass	5.98	74.00	2.04	-	-	12.45	-	-	-	Rivera et al. (2018)
Ground container glass	12.30	70.30	1.90	1.68	0.42	12.80	0.23	-	0.68	Tho-In et al. (2018)
Recycling facility glass	8.85	71.65	2.12	7.55	0.16	0.30	-	-	0.50	Zhang and Yue (2018)
By-product of industrial glass bead	9.70	72.50	0.40	3.30	0.20	13.70	0.10	-	-	Redden and Neithalath (2014)
Window glass	8.77	74.40	1.34	-	-	11.47	-	-	-	Rivera et al. (2018)

Alkali Content



Strength of stabilised Soil



Waste glass source	Other raw materials of binders	Activator Types	Specimen size (mm^3)	The highest compressive strength (MPa)	Other comments	Ref.
Mixed color glass	None	$NaOH/Na_2CO_3$ $NaOH/Na_2CO_3$ + glass Waterglass NaOH	10 × 10 × 250	˜89 (28d)	Higher total porosity	Torres-Carrasco and Puertas (2017)
Urban waste glass	Slag	NaOH $NaOH/Na_2CO_3$ Na_2CO_3	25 × 25 × 25	76.9 (180d)	-	Martinez-Lopez and Escalante-Garcia (2016)
Waste bottle glass	None	NaOH KOH	40 × 40 × 160	60.2 ± 2.14 (56d)	-	Cyr et al. (2012)
By-product of industrial glass beads	FA, slag and metakaolin (MK)	NaOH	50 × 50 × 50	32 (1d)	The enhancement of moisture stability	Redden and Neithalath (2014)
Waste bottle glass	MK	NaOH	50 × 50 × 50	35 (7d)	-	Pascual et al. (2014)
Waste bottle glass	FA and slag	NaOH	40 × 40 × 160	33 (28d)	-	Zhang et al. (2017b)
Unspecified	CACs	NaOH	50 × 50 × 50	87	Lower extent of efflorescence by adding CACs	Vafaei and Allahverdi (2016)
Recycling facility glass	Slag	NaOH + waterglass	40 × 40 × 160	67.8 (28d)	Higher resistance to sulfate attack	Zhang and Yue (2018)
Waste bottle glass, window glass and lamp glass	None	NaOH	20 × 20 × 20	56 (7d)	The reduction of compressive strengths to 28 days	Tho-In et al. (2018)

THANK YOU