第29屆近代工程技術討論會

新一代的綠色低碳建材

The New Generation Green and Low-Carbon Building Materials

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2050 Net-zero Transition
淨零轉型

Cooperating with the world and striving for a net-zero future together

十二項關鍵策略

資料來源：國家發展委員會
https://www.ndc.gov.tw/en/Content_List.aspx?n=B927D0EDB57A7A3A&upn=A2B386E427ED5689

2

Largest Source of CO_2 Produced by Industry

Steel Making

https://www.howden.com/

Thermal Power Generation

https://www.thenewslens.com/article/164239

Cement Industry

https://www.beumergroup.com/i/cement/

The total volume of cement production worldwide amounted to an estimated 4.1 billion tons in 2022

520 Kg CO2 / ton cement

4.1 billion tons CO2 / year

3

$5CaCO_3 + 2SiO_2 \Rightarrow (3CaO,SiO_2)(2CaO,SiO_2) + 5CO_2$

- 1 tonne of O.P.C. generates
- 0.55 t. of CO_2 chemistry + 0.40 t. of CO_2. fuel
- To simplify: *1 t of Portland cement = 1 t of CO_2.*

How to solve above problem?

Potential to solve or replace cement in both structural and non-structural applications

A new generation of green low-carbon material

Geopolymer Materials

無機聚合材料

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What is Geopolymer ?

無機聚合材料

- Geopolymers are kinds of inorganic polymers
- Similar to natural zeolite minerals
- A class of three-dimensionally networked alumino-silicate materials.

Other Related Name：

Mineral Polymer
Geopolymeric Materials
Aluminosilicate Polymer
Inorganic Polymeric Materials

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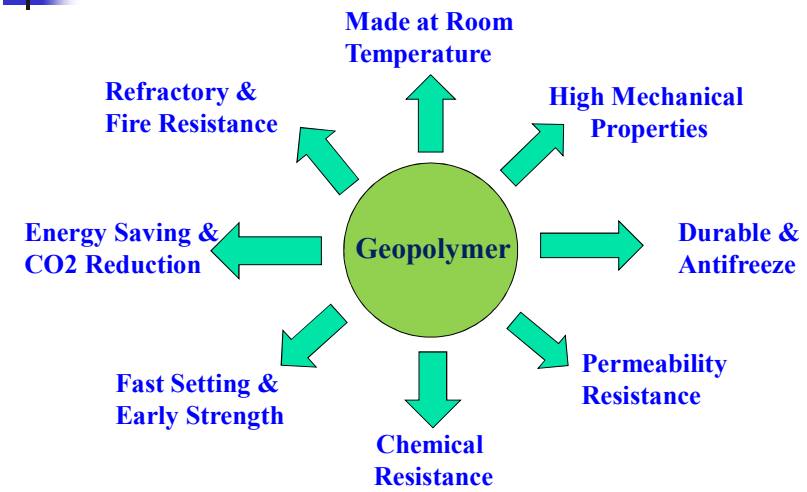
The Excellent Properties of Geopolymer



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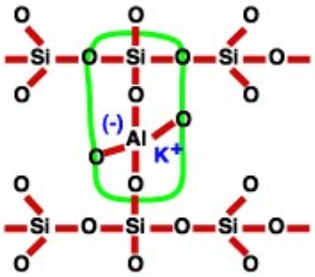
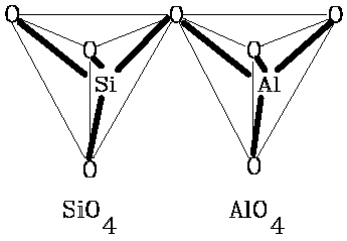
Geopolymers - Basic Structure

$M_n\{-(SiO_2)_z-AlO_2\}_n \cdot wH_2O$





Davidovits, J., 1999, Chemistry of Geopolymeric Systems Terminology, Proceeding of Geopolymer, 99 Second International Conference, France, pp. 9–37.

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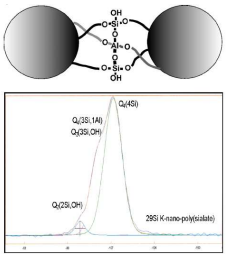
Chemical Reaction



$$n(Si_2O_5,Al_2O_2) + 2nSiO_2 + 4nH_2O + NaOH \text{ or } (KOH) \rightarrow Na^+,K^+ + n(OH)_3\text{-Si-O-Al}^-\text{-O-Si-}(OH)_3$$

(Si-Al materials)

$(OH)_2$

(Geopolymer precursor)

(1)

$$n(OH)_3\text{-Si-O-Al}^-\text{-O-Si-}(OH)_3 + NaOH \text{ or } (KOH) \rightarrow (Na^+,K^+)\text{-(-Si-O-Al}^-\text{-O-Si-O-)} + 4nH_2O$$

$(OH)_2$ O O O

(Geopolymer backbone)

(2)

Xu H. and Van Deventer, J.S.J., The geopolymerisation of alumino-silicate minerals, International Journal Minerals Process, Vol. 59, pp. 247-266, 2000.

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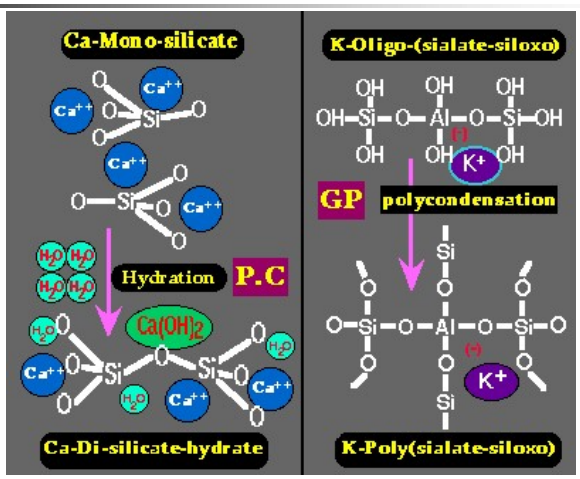
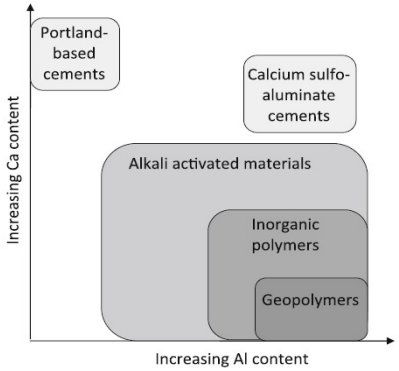
Chemical Reaction of Portland Cement & Geopolymer



Davidovits, J., 1999, Chemistry of geopolymeric systems terminology, Proceeding of Geopolymer"99 Second International Conference, Editors: Davidovits, J., Davidovits, R. and James, C., France, pp. 9-37

9

What is the difference between Geopolymer and Alkali Activated Material (AAM)? (1)



Geopolymer is a subset of AAM & inorganic polymers

Geopolymer

Ca ↓ ; Al ↑

AAM

Ca ↑ ; Al ↓

Van Deventer, J. S.; Provis, J. L.; Duxson P.; Brice, D. G., 2010, Chemical research and climate change as drivers in the commercial adoption of alkali activated materials. Waste and Biomass Valorization, 1(1), 145-155

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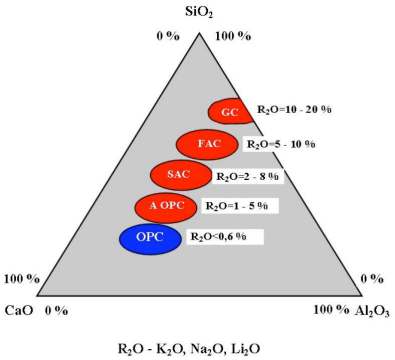
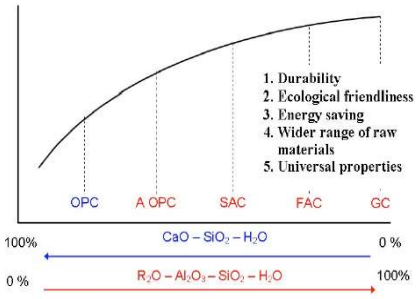
What is the difference between Geopolymer and Alkali Activated Material (AAM)? (2)





Krivenko P., 2002, Alialine cement: From research to application, Proceedings of the Int. Conf. Geopolymer 28th–29th October 2002

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Mixing Procedure

+

Recipe

Mixing

Casting

Curing & Condensation

Products

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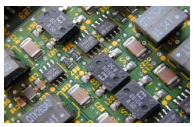
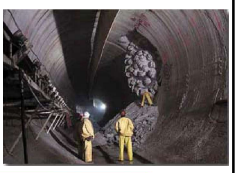
Applications of Geopolymer

- Building Materials
- Fire Resistance Materials
- Concrete Reinforcement
- Heat Insulation
- Ceramics
- Chemical Industry
- Tunneling
- Decoration Materials
- Arts
- Waste Reutilization







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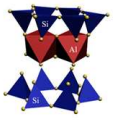
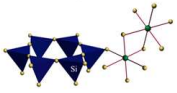
Applications of Geopolymer

- Waste Treatment & Recycling
  - Solidification/Stabilization Hazardous Waste
  - Adsorption Heavy Metals
  - Radioactive Materials Treatment
  - Recycling various types of waste





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2013 – The world's first Geopolymer Green Cement Building (University of Queensland, Australia)



UQ's Global Change Institute


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2014 -- Brisbane West Wellcamp Airport, Australia

(Use of 30,000 m^3 Geopolymer Green Concrete)


Saved some 8,640 tonnes of CO2 emissions in this project alone



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Australia

WAGNERS
COMPOSITE FIBRE TECHNOLOGIES

Earth Friendly Concrete (EFC)

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USA

GEOPOLYMERSOLUTIONS

Milliken
GeoSpray™
Geopolymer Mortar

EcoCast™

Milliken Infrastructure Solutions, LLC

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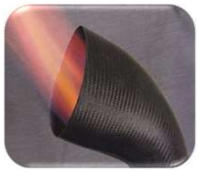
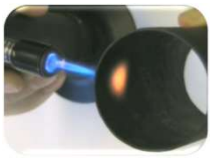
France

Pyromeral Systems

NéoTerre





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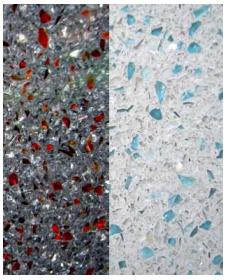
Czech Republic



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China

機場	抗彎強度(MPa)
	4小時>
西藏邦達機場	4
西藏日喀則機場	3.2
新疆某直升機機場	3.1
新疆武警直升機機場	3.3

(曾定國等人，快凝早強無機聚合混凝土研究及應用，北京，科學出版社，2015)

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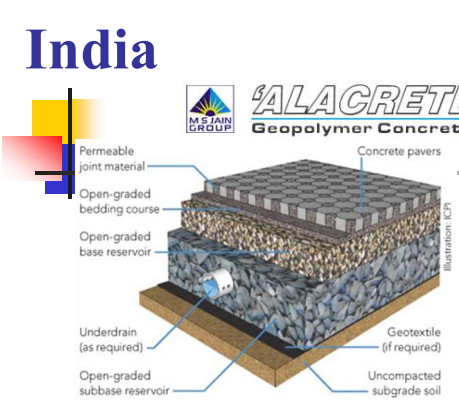
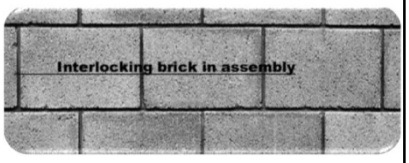
India





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Geopolymer Technology

Ceramics

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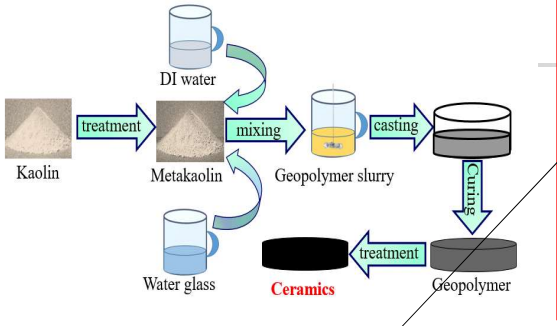
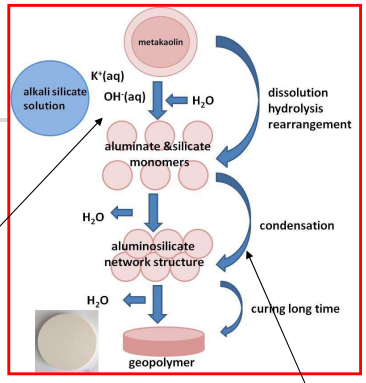
Potassium-based (KGP) Ceramic Material Preparation





$[Al(OH_2)_4]^{3+} + 4H_2O \rightarrow [Al(OH_4)]^- + 4H_3O^+$
$[Al(OH_2)_4]^{3+} + 5H_2O \rightarrow [AlO(OH)_3]_2^- + 5H_3O^+$
$[Al(OH_2)_5]^{3+} + 4H_2O \rightarrow [Al(OH)_4(OH_2)]^- + 4H_3O^+$
$[Al(OH_2)_5]^{3+} + 5H_2O \rightarrow [Al(OH)_5]_2^- + 5H_3O^+$
$[Al(OH_2)_6]^{3+} + 4H_2O \rightarrow [Al(OH)_4(OH_2)_2]^- + 4H_3O^+$
$[Al(OH_2)_6]^{3+} + 5H_2O \rightarrow [Al(OH)_5(OH_2)]_2^- + 5H_3O^+$
$[Si(OH_2)_4]^{4+} + 5H_2O \rightarrow [SiO(OH)_3]^- + 5H_3O^+$
$[Si(OH_2)_4]^{4+} + 6H_2O \rightarrow [SiO_2(OH)_2]_2^- + 6H_3O^+$

溶解反應

$[Al(OH)_4]^- + [SiO_2(OH)_2]^{2-} \rightarrow [(OH)_3Al\text{-}SiO_2(OH)]^{3-} + H_2O$
$[Al(OH)_4]^- + [(OH)_3Al\text{-}SiO_2(OH)]^{3-} \rightarrow [Al_2(OH)_6SiO_4]^{4+} + H_2O$
$[Al(OH)_4]^- + [SiO(OH)_3]^- \rightarrow [(OH)_3Al\text{-}SiO(OH)_2]^{2-} + H_2O$
$[(OH)_3Al\text{-}O\text{-}SiO(OH)_2]^{2-} + [SiO(OH)_3]^- \rightarrow [Al(OH)_2Si_2O_4(OH)_4]^{3-} + H_2O$
$[Al(OH)_2Si_2O_4(OH)_4]^- + [SiO(OH)_3]^- \rightarrow [Al(OH)Si_3O_6(OH)_6]^{4+} + H_2O$
$[Al(OH)Si_3O_6(OH)_6]^{4+} + [SiO(OH)_3]^- \rightarrow [AlO_4Si_4O_4(OH)_8]^{5+} + H_2O$
$[(OH)_3Al\text{-}O\text{-}SiO(OH)_2]^{2-} + [SiO_2(OH)_2]^{2-} \rightarrow [Al(OH)_2Si_2O_4(OH)_3]^{4+} + H_2O$
$[Al(OH)_2Si_2O_4(OH)_3]^{4+} + [SiO(OH)_3]^- \rightarrow [Al(OH)Si_3O_6(OH)_5]^{5+} + H_2O$
$[Al(OH)Si_3O_6(OH)_5]^{5+} + [SiO(OH)_3]^- \rightarrow [AlO_4Si_4O_4(OH)_7]^{6+} + H_2O$
$[Al(OH)_2Si_2O_4(OH)_3]^{4+} + [SiO_2(OH)_2]^{2-} \rightarrow [Al(OH)Si_3O_7(OH)_4]^{6-} + H_2O$
$[Al(OH)Si_3O_6(OH)_5]^{5+} + [SiO_2(OH)_2]^{2-} \rightarrow [AlO_4Si_4O_5(OH)_5]^{7+} + H_2O$

再聚合反應

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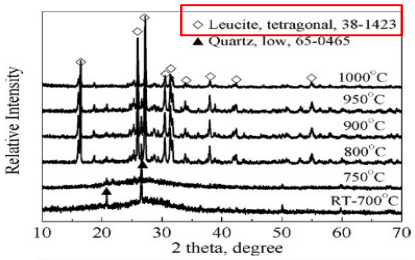
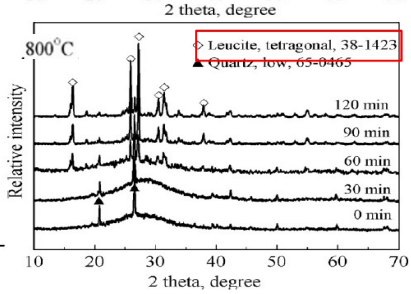
Leucite Ceramics directly derived from Geopolymer Precursors

2°C/min from RT to 600°C and
5°C/min from600°C to 1000°C.





Specimen	Flexural strength (MPa)	Young's modulus (GPa)	Fracture toughness (MPa · $m^{1/2}$)	Vickers hardness (GPa)
KGP	12.3±1.2	10.3±1.2	0.2±0.04	0.68±0.04
Leucite ceramic	70.0±6.8	65.0±6.3	1.3±0.16	7.39±0.24

PG He, DC Jia, et al, Ceramics International, 37 (2011) 59-63.
PG He, DC Jia, et al, Journal of the European Ceramic Society, 33 (2013) 689-698.

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Geopolymers ⇨ converted into a variety of Ceramic Materials

Geopolymer

- Zeolite/Pollucite — Hydrothermal Treatment
- Leucite of high CTE — Upon Heating
- Pollucite of low CTE — Li *Partial Substitution for* Cs
- Celsian Ceramics — Ba/Sr *Ion Exchange*
- SiC & AlN — C *Thermal Reduction*

[1] PG He, DC Jia, et al, Ceramics International, 36 (2010) 2395-2400.
[2] PG He, DC Jia, et al, Ceramics International, 37 (2011) 59-63.
[3] PG He, DC Jia, et al, Journal of Materials Science, 48 (2013) 1812-1818.
[4] PG He, DC Jia, et al, Journal of the European Ceramic Society, 33 (2013) 689-698.
[5] JK Yuan, PG He, et al, Journal of the American Ceramic Society, 99 (2016) 3784-3791.
[6] PG He, S Fu, et al, Journal of the European Ceramic Society, 37 (2017) 4179-4185.
[7] JK Yuan, PG He, et al, Journal of the American Ceramic Society, 100 (2017) 4412-4424.
[8] JK Yuan, PG He, et al, Ceramics International, 44 (2018) 10047-10054.
[9] S Fu, PG He, et al, Journal of the European Ceramic Society, 39 (2019) 563-573.
[10] DC Jia, YH Li, PG He, et al, Ceramics International, accepted

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Domestic Development of Geopolymer Green Cement and Concrete

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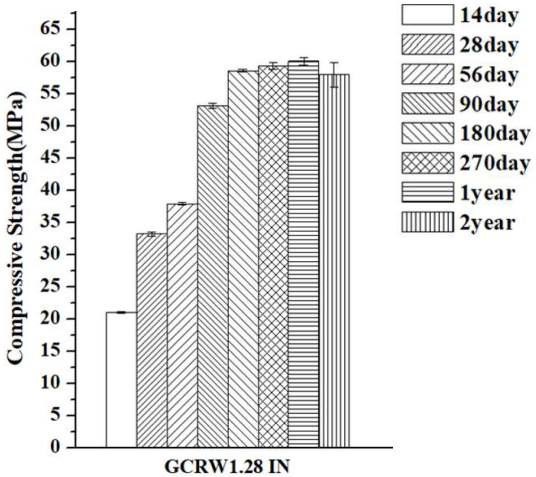
Geopolymer Green Concrete Strength Analysis



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Ready-Mixed Geopolymer Concrete & Construction in Dongshan Ilan Experimental Community, Taiwan

6th October, 2017

宜蘭縣冬山鄉
賓志預拌混凝土廠

BIN JYH Ready-Mixed Plant
in Dongshan Ilan
Taiwan

6th October, 2017

Slump ：270 mm
Slump Flow：550*570 mm

7 d：13 MPa
28 d：22 MPa
180 d：28 MPa

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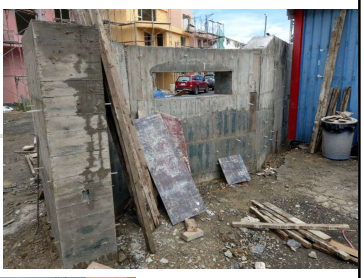
11th October, 2017



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May, 2018




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Ready-Mixed Geopolymer Mortar & Construction in Taipei Tech, Taiwan

5th October, 2019

Slump : 260 mm
Slump Flow : 480*460 mm

Setting Time :
Initial : 4.2 h
Final : 23 h

Compressive Strength
3d : 9.5 MPa
7d : 35.6 MPa
28d : 39.9 MPa

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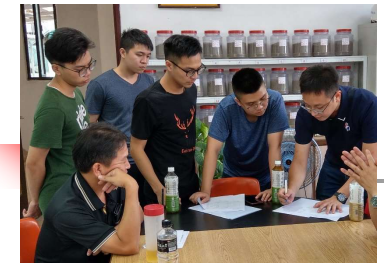
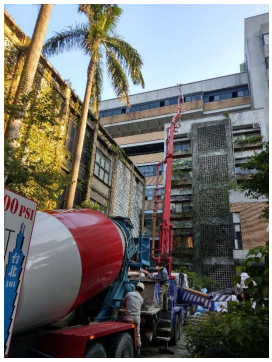


Discussion proportion before mixture

Operation in Control Room

Pumping Alkali Solution



On-site pumping to 9th floor

35

Workability after 45 minutes

260 mm

480*460 mm

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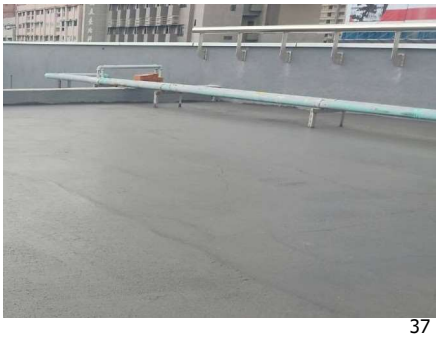
Construction Photos



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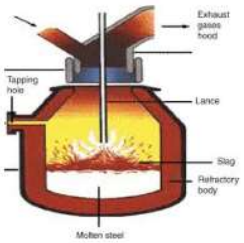
Stabilization/Reutilization of Basic Oxygen Furnace (BOF) Slags using Geopolymer Technology

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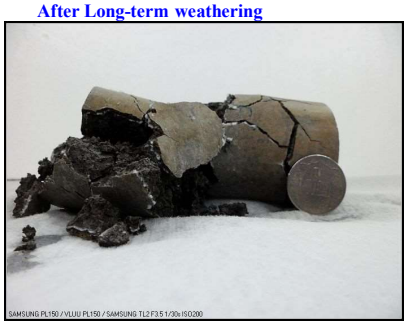
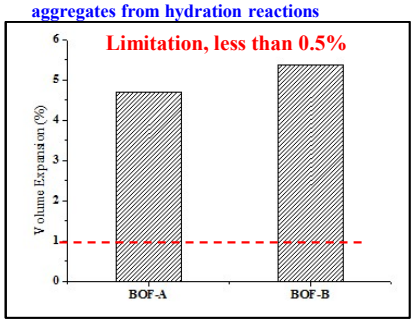
The Problem for Recycling of Basic Oxygen Furnace (BOF) Slags

Expansion in OPC system

BOF-based Portland Cement Mortar
After Long-term weathering



CNS 15311
Method of test for potential expansion of aggregates from hydration reactions



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BOF-Based Portland Cement Mortar

	Before Autoclave Treatment	After Autoclave Treatment
Original BOF slag Aggregate (< 4 mesh) (Portland Cement System)		
BOF slag Aggregate Treated by Oxalic Acid (< 4 mesh) (Portland Cement System)		

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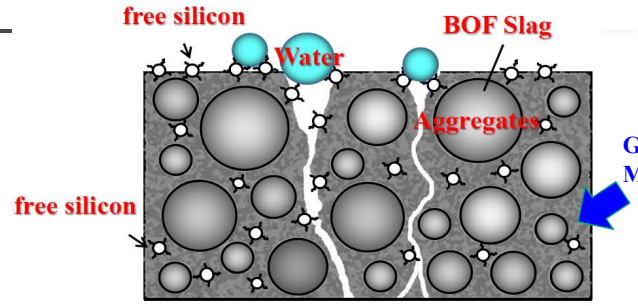
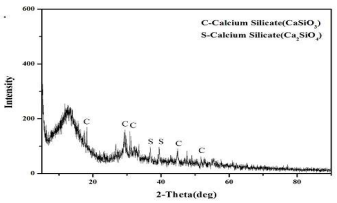
New Concept to Prevent the BOF slags Expansion



Large amounts of free Si in geopolymer matrix

$CaO + SiO2 = CaSiO3$
$MgO + SiO2 = MgSiO3$



XRD results after autoclave test

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Solidification/ Stabilization of Basic Oxygen Furnace (BOF) Slags

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Autoclave Test : 215 ℃, 2MPa, 3h

Strict Test method

C-B-7days
< 4 mesh BOF slag in OPC
Volume Expansion Rate: Fail

Before Autoclave Test

After Autoclave Test

BG-7days
< 4 mesh BOF slag in Geopolymer Cement
Volume Expansion Rate: 0.35%

Before Autoclave Test

After Autoclave Test

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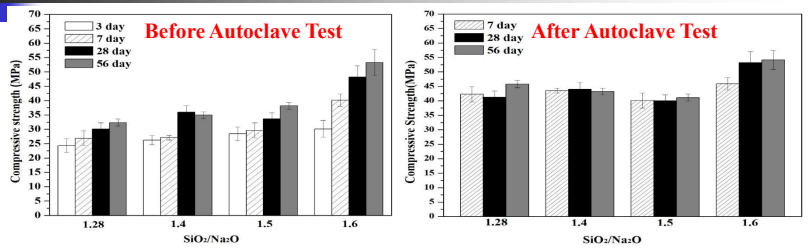
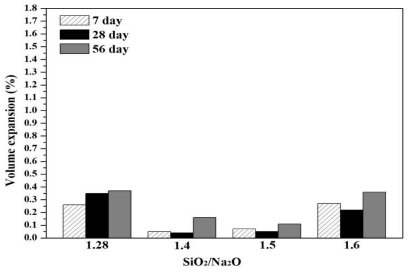
Effect of SiO_2/Na_2O Molar Ratio on Compressive Strength



Before

After



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First Ready-Mixed Plant Test

Stablization BOF slags using Geopolymer Technology

MPLab

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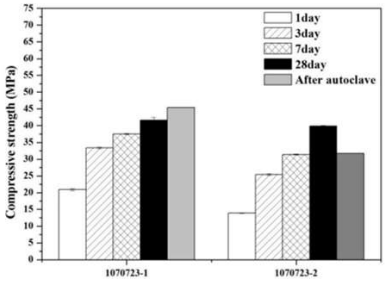
First Test
Compressive Strength & Autoclave Tests

MPLab

Test Item		Slump (cm)	Slump Flow (cm)	Compressive Strength (MPa)									After CNS 1258	
Date				1d		3d		7d		28d		After Autoclave	7d	28d
1070723-1	GP 5:5	26	38	20.3 21.5	20.9	33.9 32.8	33.4	37.2 37.9	37.5	39.7 43.4	41.6	45.4	Burst point	Good
1070723-2	GP 6:4	27	51	13.8 14.1	13.9	24.9 26.0	25.4	31.6 31.1	31.4	39.7 40.4	39.9	31.7	Burst point	Good



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Filling 1 M^3 Test Body

MPLab

Slump ：270 mm
Slump Flow：510*490 mm
Compressive Strength
1day：20.0 MPa
3day：32.1 MPa
7day：36.1 MPa
28day：40.8 MPa

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Making New Jersey's Guardrail

MPLab

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Second Ready-Mixed Plant Test

Stablization BOF slags using Geopolymer Technology

27 September, 2018

MPLab

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Second Test

Compressive Strength & Autoclave Tests

MPLab

Test Item		Slump	Slump Flow	Compressive Strength (MPa)		
Date		(cm)	(cm)	7d	28d	28d After Autoclave test
1070927-1	GP 1	23.5	36*37	19.4	31.2	34.5
1070927-2	GP 2	18.5	---	37.2	19.3	18.5
1070927-3	GP 3	21	31*32	29.3	43.9	20.2

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Making 1 M^3 Test Body & New Jersey's Guardrail

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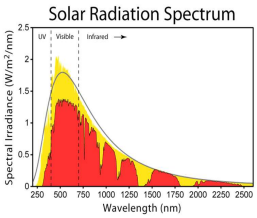
Other Research Works



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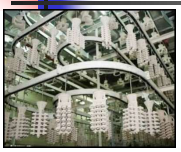
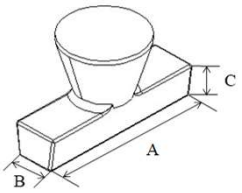
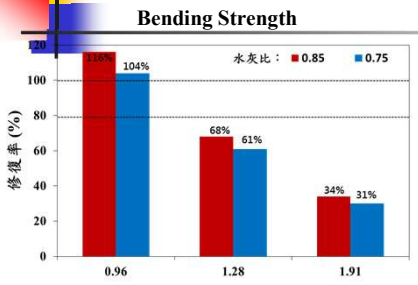
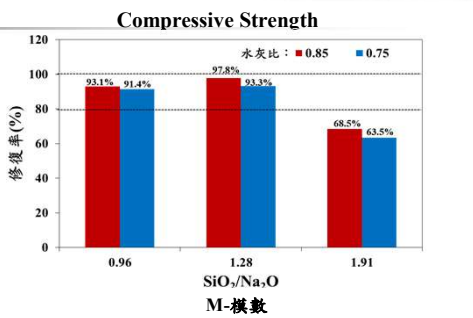
Recycled ceramic shell mould as refectory coating materials for investment casting

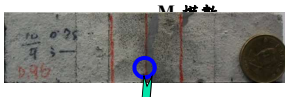


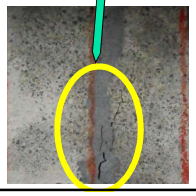


Geopolymer Cement for Concrete Repair









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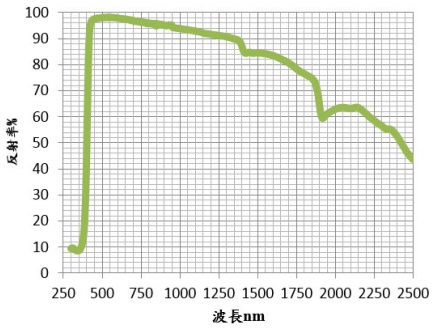
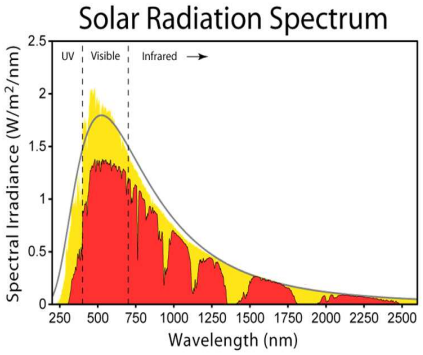
Thermal Insulation Coating

Metakaolin Based Geopolymer +
Functional Powders

Visible light 390-700nm Ave Reflectivity 94%
Near infrared light 700-2000nm Ave Reflectivity 85%

Full spectrum 390-2000nm Ave Reflectivity 87%





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Geopolymer Antirust Coating

Metakaolin Based Geopolymer +
Functional Powders

Salt Spray Test ：3000 hours

Coating Thickness : 500 um

鹽水噴霧試驗機
(5%W/V氯化鈉 恆溫恆濕)

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Heavy metal adsorption characteristics on metakaolin-based geopolymer

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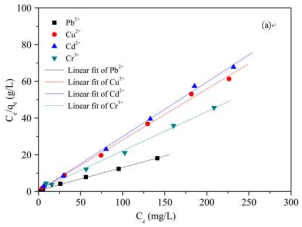
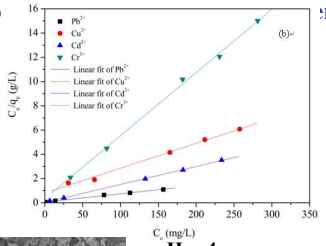
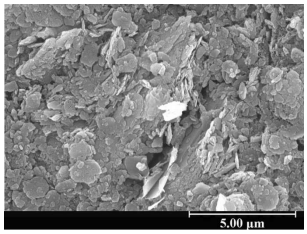


pH < 2



pH = 4



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Solidification/ Stabilization of Incinerator Fly Ash by Geopolymer Technology

TCLP Leaching Tests

Elements	MSWI FA	7days			14 days			28 days			Standard value
		SiO_2/Na_2O			SiO_2/Na_2O			SiO_2/Na_2O			
		0.96	1.28	1.91	0.96	1.28	1.91	0.96	1.28	1.91	
Ba	3.6	0.2	0.7	0.4	0.2	1.0	0.5	N.D	N.D	N.D	100
Zn	21.3	N.D	1.18	N.D	N.D	N.D	N.D	N.D	N.D	N.D	-
Pb	60.2	N.D									5
Cd	N.D	N.D									1
Cr	N.D	N.D									5
Cu	≤ 0.1	N.D									15
	N.D：non detected. Unit：mg/L										

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Fire Resistance & Light Weight Heat Resistance Materials

Using Perlite, Expanded Vermiculite, Foam Glass to make Light weight Fire/Heat Resistance Materials

- Fire Resistance Temperature >1100℃
- Thermal Conductivity < 0.6 W/mK

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Cold-Bonded Light Weight Aggregate

Ceramsite

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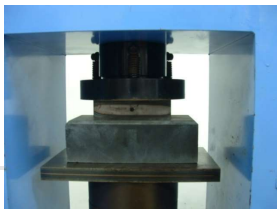
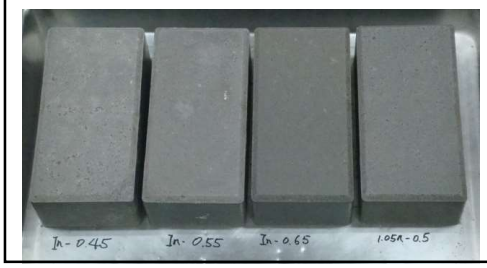
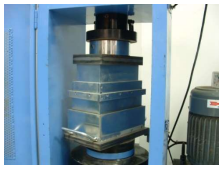
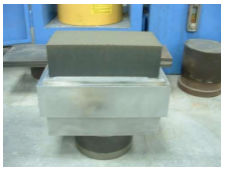
Cold-Bonded High Pressure Brick









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Fabrication Artificial Aggregate

Sludge Fly Ash

RDF Fly Ash

Made Geopolymer

Crushing

Made Concrete or CLSM

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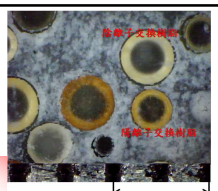
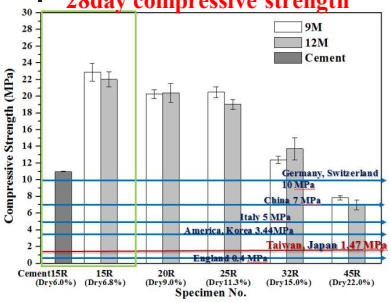


Solidification of Radioactive Granular Ion-Exchange Resins

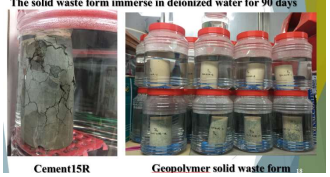
2mm

28day compressive strength



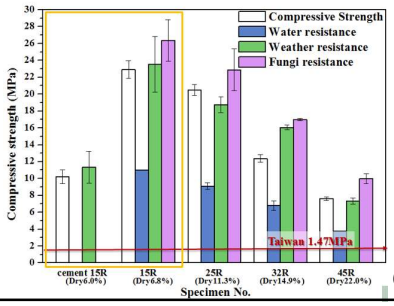
Water-resistance test According to FCMA-WFC-510

The solid waste form immerse in deionized water for 90 days



Cement15R Geopolymer solid waste form

The free liquid proportion of geopolymer solid waste form is 0



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Summary

- Geopolymer ➪ New Low-Carbon Building Materials
- Geopolymer Technology can be used in different fields.
- There are many application areas still worth developing.
- Geopolymer Technology needs everybody to carry it forward.

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Thank you for your attention

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