Fundamentals of Geopolymers

By

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8th June 2020 11.00AM

Webinar Series

Indian Concrete institute, Bengaluru Centre

Cement Concrete

will remain as Very popular material

Good in compression

More advantages

Per capita Usage is next only to water

Each ton releases equal amount of CO_2

Need of alternative material

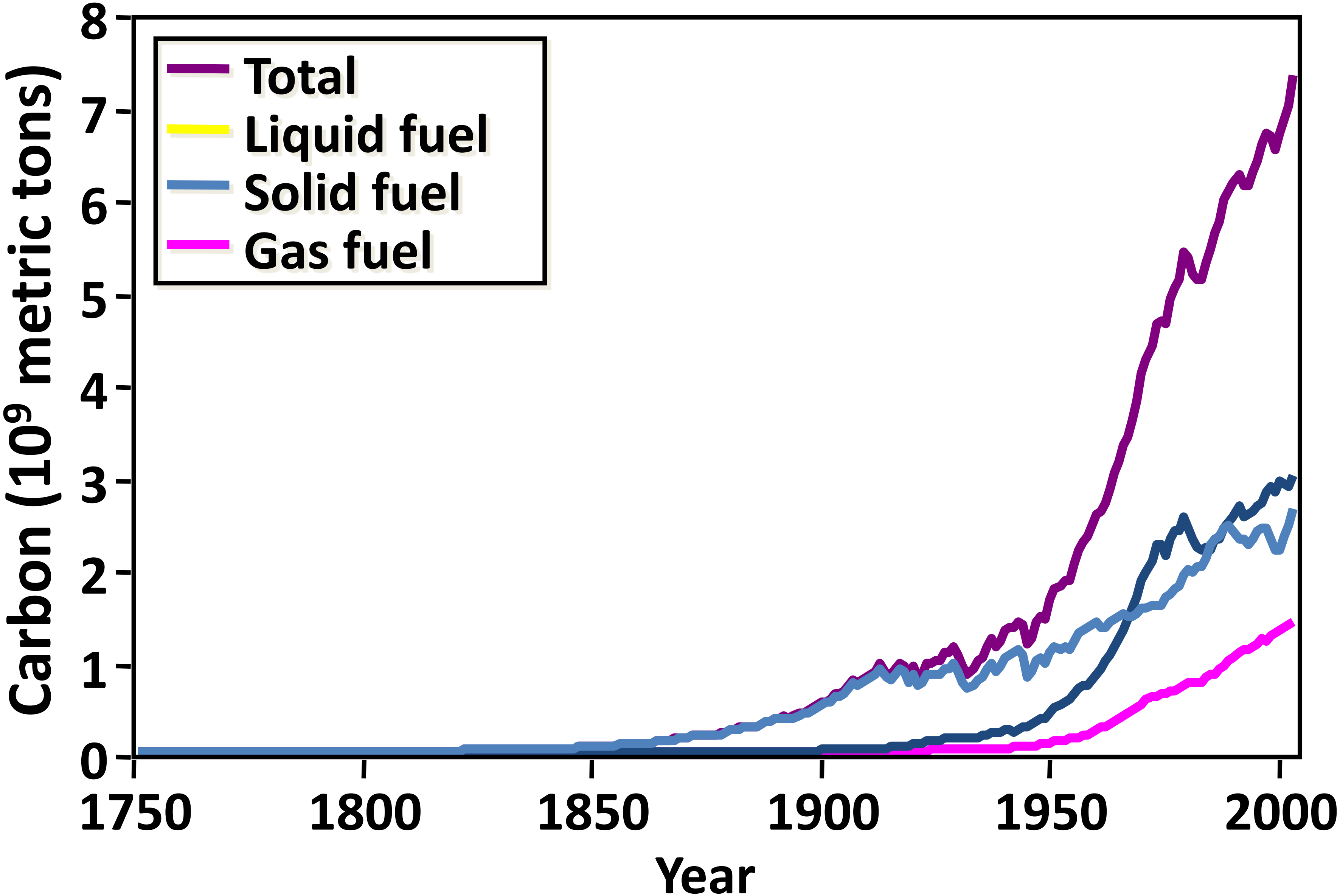
Portland cement

- Most energy intensive
- consumes 4GJ per tonne of energy
- Major ingredient of concrete
- Less shelf life

Cementicious Materials

- Different cementicious composites -using Industrial waste/Marginal
- Fly ash, GGBFS, Lime, Gypsum, etc.
- Potential to use as alternatives to OPC
- Using in construction = the best way to dispose

Worldwide Carbon Emissions

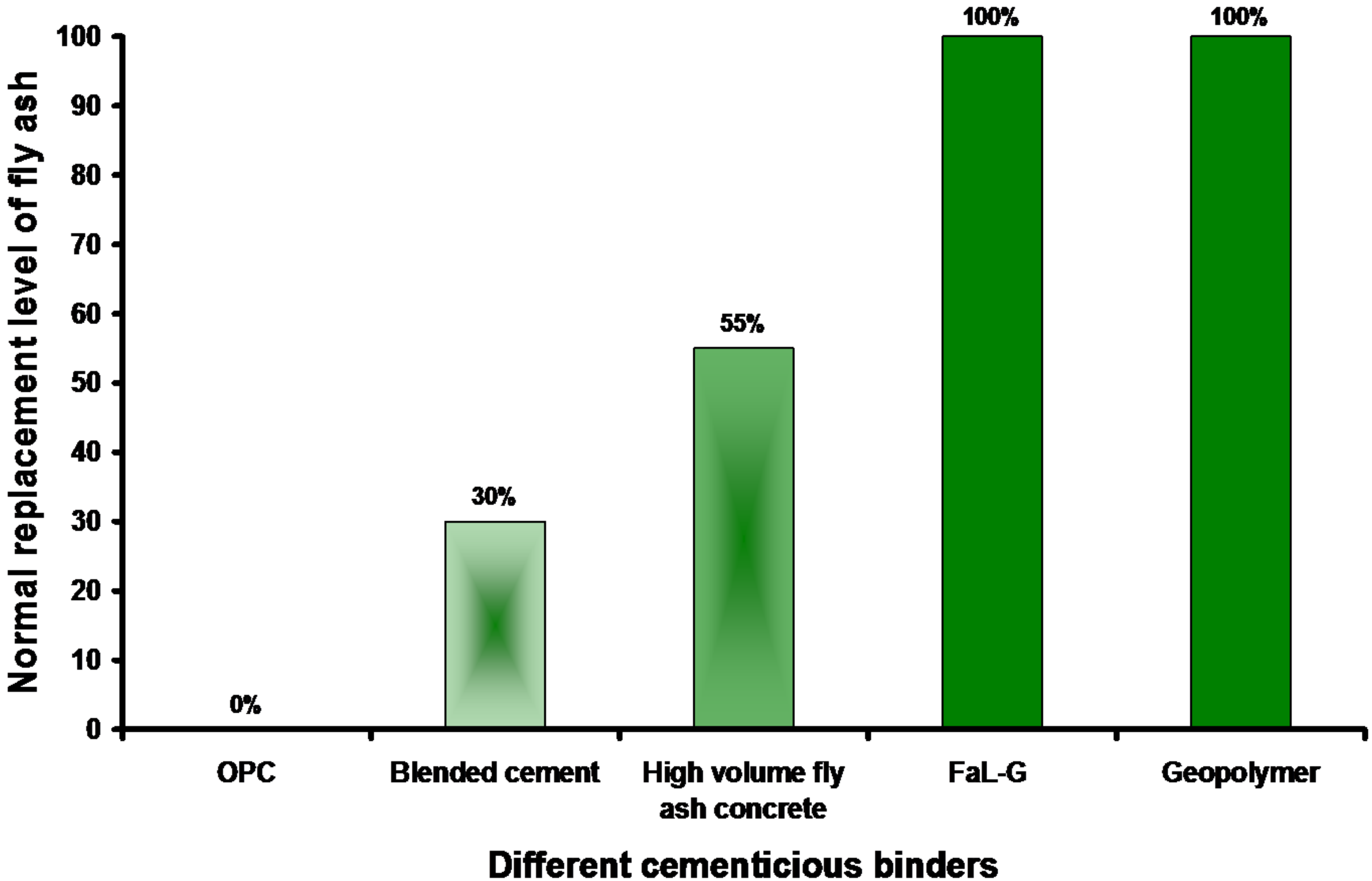


Mitigation of Global Warming

- Conservation
  - Reduce energy needs
  - Recycling
- Alternate energy sources
  - Nuclear
  - Wind
  - Geothermal
  - Hydroelectric
  - Solar
  - Fusion?

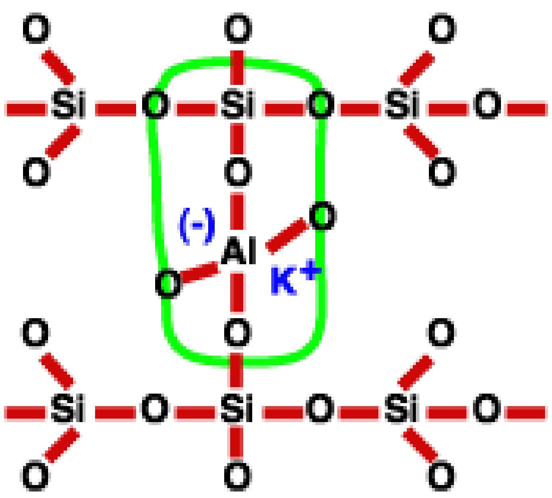
How it is possible in Construction industry?

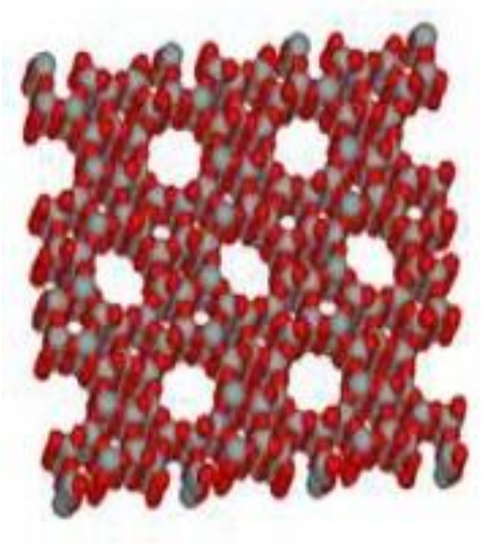
Replacement of OPC by fly ash in different materials



What is geopolymer?

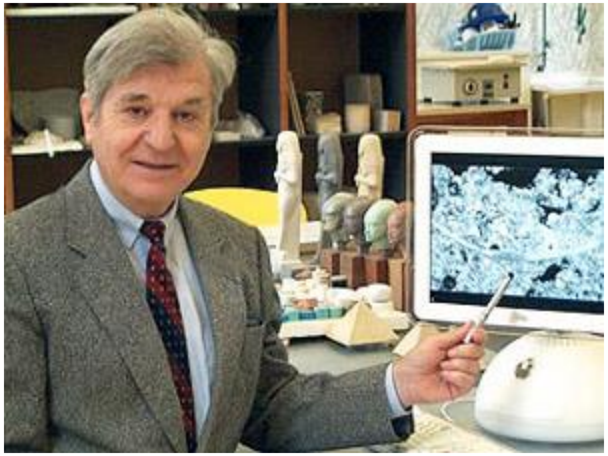
- Activation of natural materials – clay etc
- Geo = available in earth's crust
- Polymerization – cementing material
- Low carbon foot prints

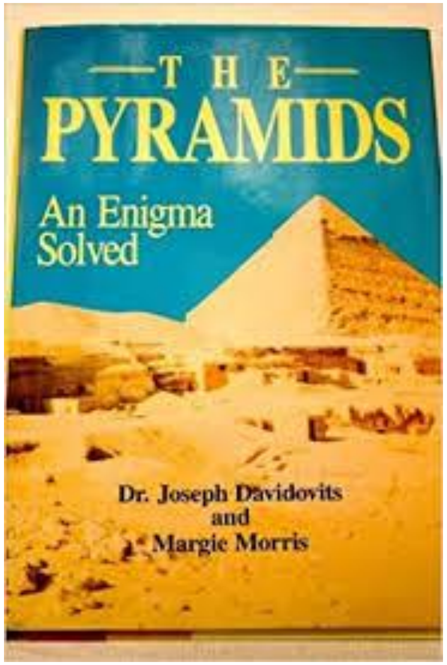




Prof. Joseph Davidovtis

French Scientist
Pyramids in Egypt
Postulated a theory – 4500 years
Controversial





Coal ash

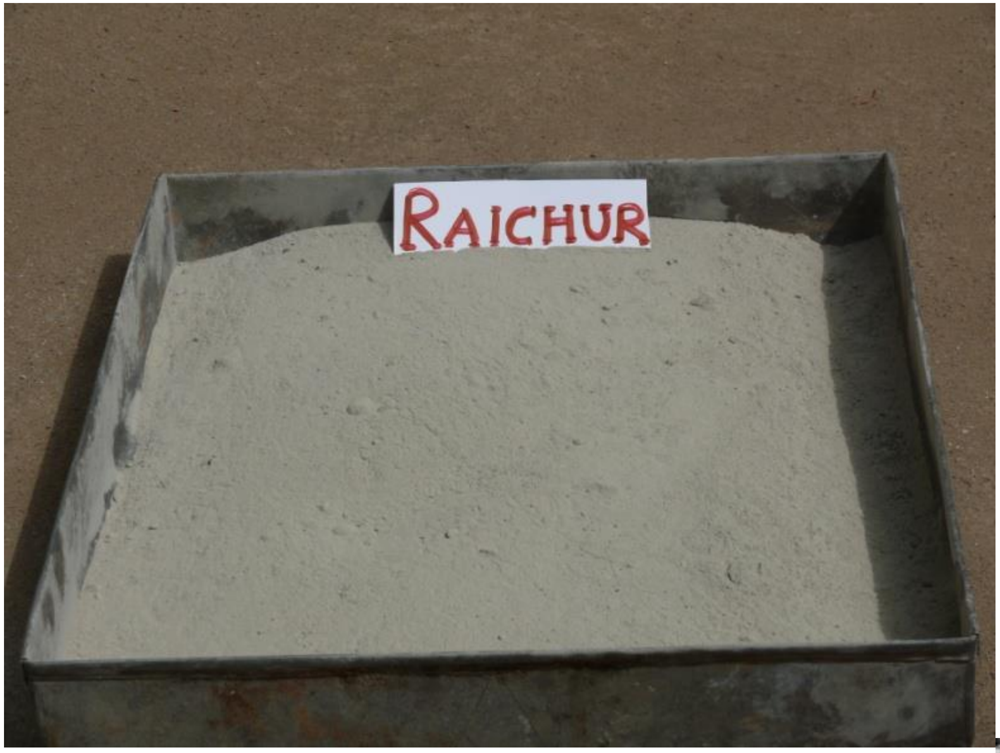
India-Electricity- 65% coal burning

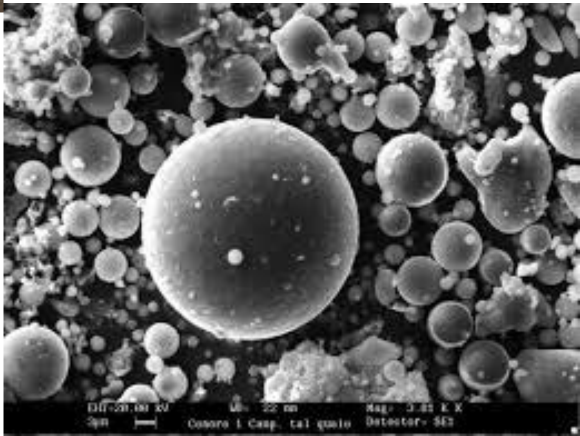
Coal reserves expected to last

>100 years.

Fly ash

Fly ash



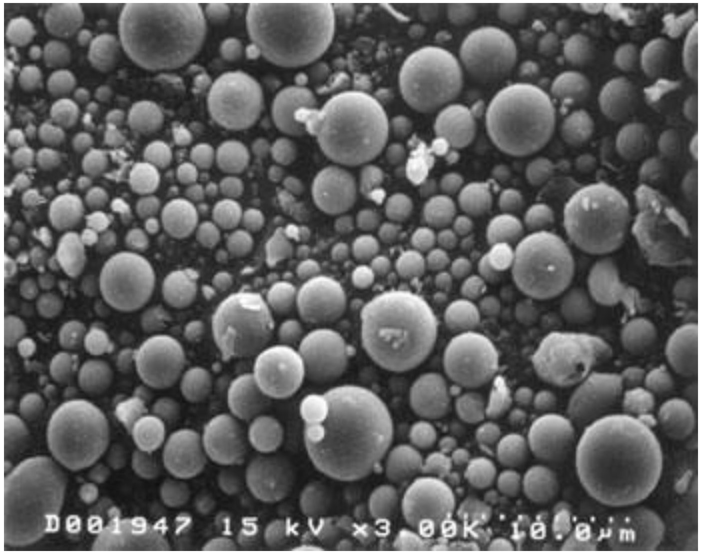


By product of TPS
Rich in Si and Al
Finer than cement
Spherical in shape
Can replace cement

ASTM Classification of Fly ash

Class F – Ca <5% - Anthracite coal
Not self cemeticious
Very common across World

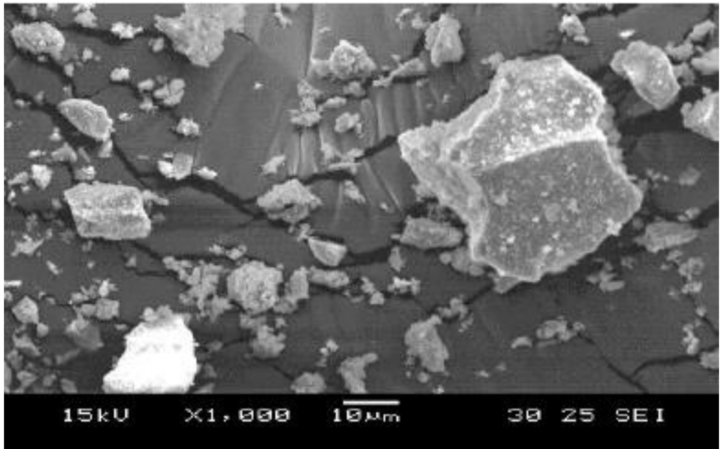
Class C - Ca>15% - Lignite coal
Self cememnticous
Rare – Lot of commercial value



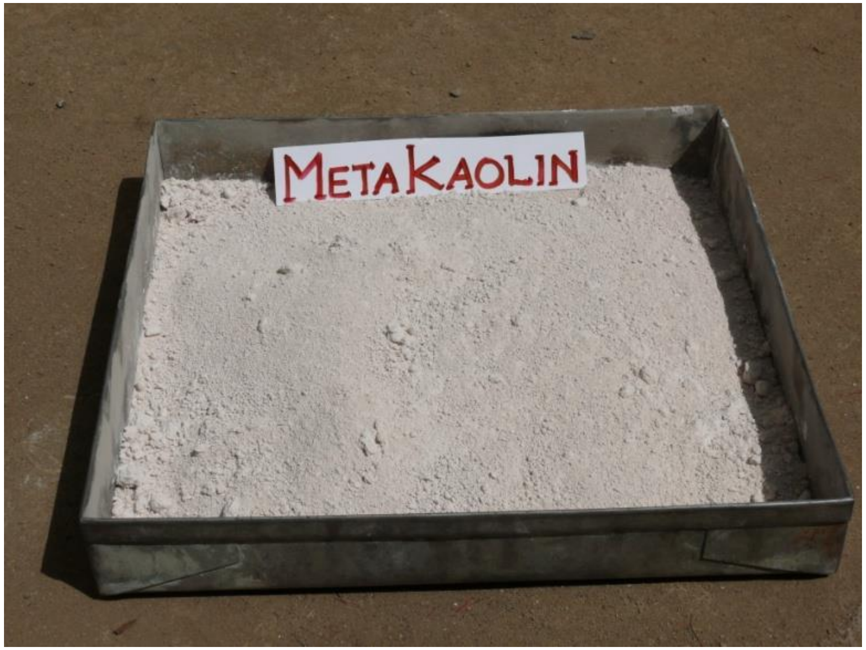
Guidance documents used for fly ash quality assurance.	
ACI 229R	Controlled Low Strength Material (**CLSM**)
ASTM C 311	Sampling and Testing Fly Ash or **Natural Pozzolans** for Use as a Mineral Admixture in Portland Cement Concrete
AASHTO M 295 ASTM C 618	Fly Ash and Raw or **Calcined Natural Pozzolan** for Use as a Mineral Admixture in Portland Cement Concrete
ASTM C 593	Fly Ash and **Other Pozzolans** for Use With Lime
ASTM D 5239	Standard Practice for **Characterizing Fly Ash** for Use in Soil Stabilization
ASTM E 1861	Guide for the Use of Coal Combustion By-Products in **Structural Fills**

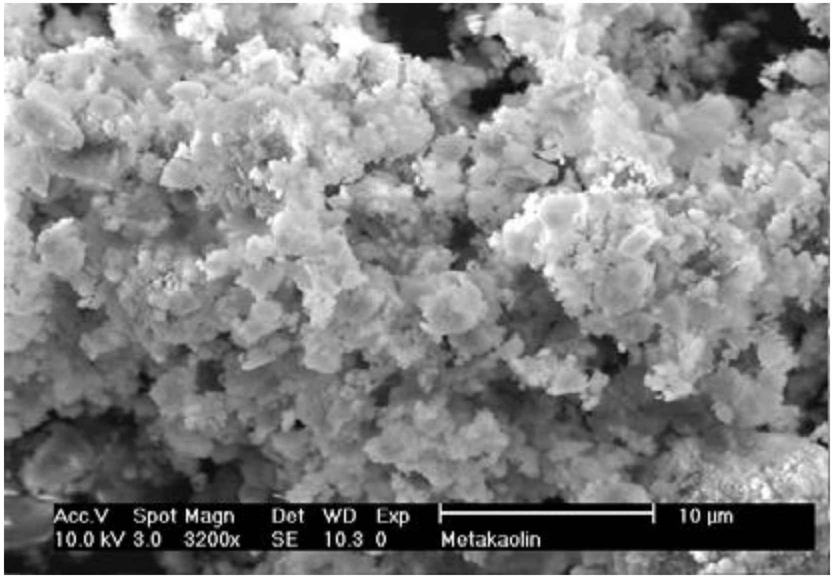
Slag

Waste from Ferrous industry
Quenched, ground, granulated – GGBS
Rich in Si, Al, Ca



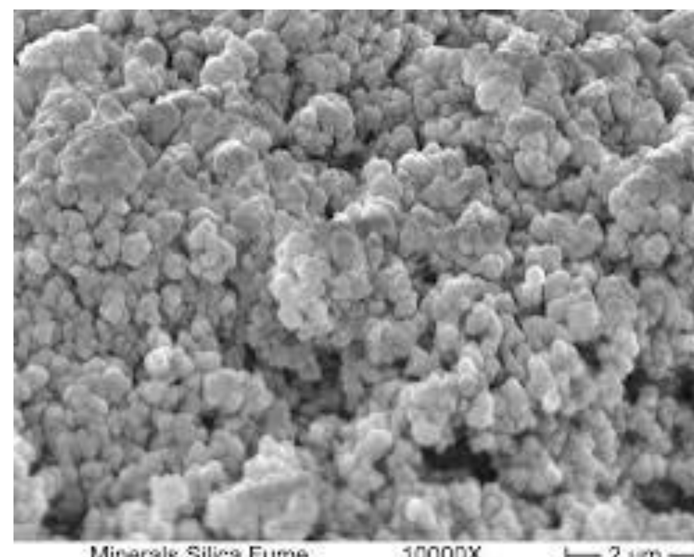
Metakaolin





Burnt clay at high temperature
Highly reactive
Contains Silica
Can replace cement
Not economical

Silica Fume



Contains >90 % Silica
Finer than Fly ash – 1 micron
Condensed form
Can replace cement

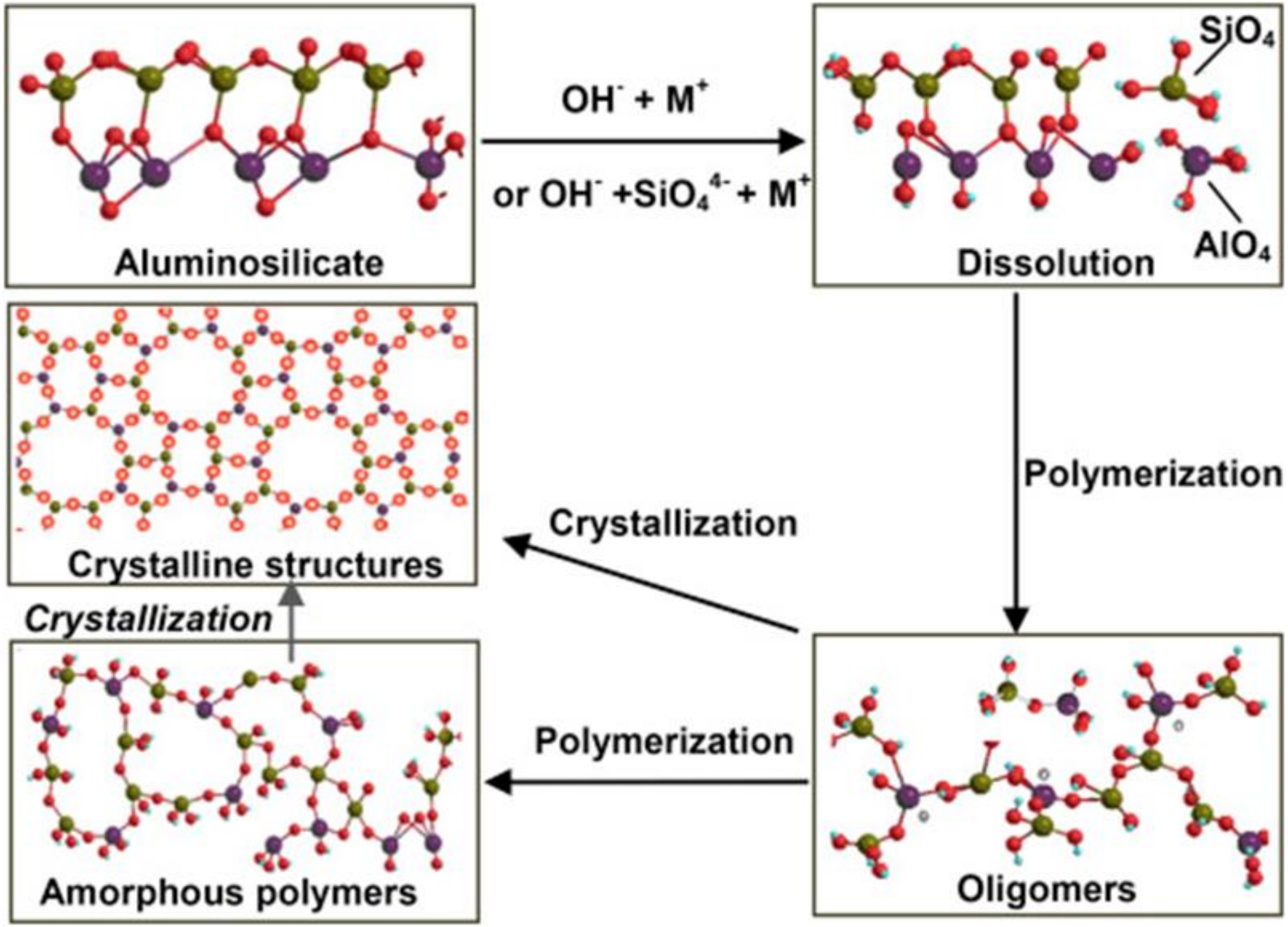
Properties of binders

Binder	Specific Gravity	Percentage Of Residue left on 45μ	Loss on Ignition	Chemical Composition in percentage							
				Al_2O_3	Fe_2O_3	SiO_2	MgO	SO_3	Na_2O	Total Chlorides	CaO
Fly Ash (FA1)	2.35	0.00	0.9	31.23	1.5	61.12	0.75	0.53	1.35	0.06	3.20
Fly Ash (FA2)	2.00	71.98	4.0	33.3	0.94	35.2	5.1	2.1	1.5	0.05	3.10
Fly Ash (FA3)	2.40	9.8	0.9	33.8	0.91	35.0	5.0	2.0	1.5	0.02	3.10
Fly Ash (FA4)	2.30	2.1	0.8	34.2	0.80	35.0	5.0	2.0	1.5	0.05	3.20
GGBFS	2.50	10.45	0.3	13.24	0.65	37.21	8.65	-	-	0.003	37.23

Ingredients of geopolymer mortar

Ingredients of Geopolymeric Mortar

Activation



Aluminosilicate
OH⁻ + M⁺
or OH⁻ +SiO₄⁴⁻ + M⁺
SiO₄
AlO₄
Dissolution
Polymerization
Crystallization
Crystalline structures
Crystallization
Polymerization
Amorphous polymers
Oligomers

Water

- Used to make alkaline solution
- Released during geopolymerrisation
- Not used for curing

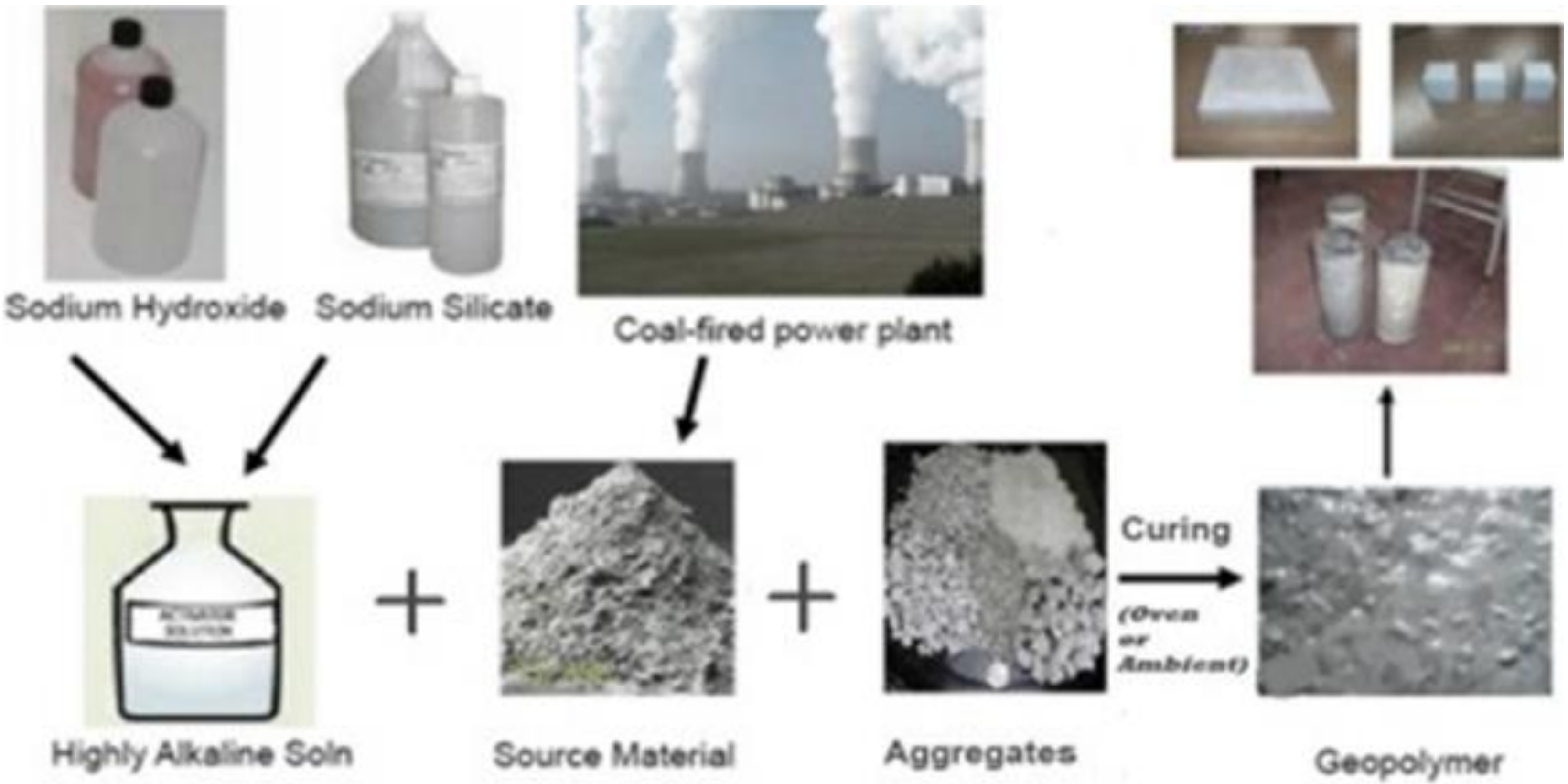
Making of Geopolymer

- Same process as cement composites
- Change in ingredients
- Cement ---→ Alumnino silicates
- Eg of Alumino silicates
  - Fly ash
  - GGBS
  - Silica fume
  - Metakolin
  - Rice husk ash
  - Red mud etc **- Locally available material**

Making of Geopolymer

- Aggregate is same
- Water -→ Alkaline solution – **8-14 M**
  - – Sodium hydroxide and sodium silicate
  - – Potassium hydroxide and Potassium silicates
  - Sodium salts +water -→ Alkaline solution

Process of making



Process - Contd

Strength Development

- **Fly ash class F**

  Geopolymerisation

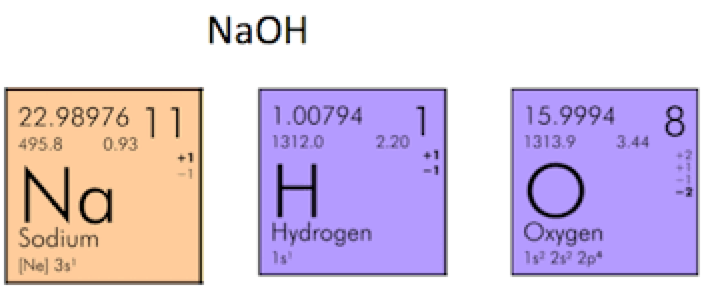
  At elevated temperature – 60 ^{O}C
- **GGBS**

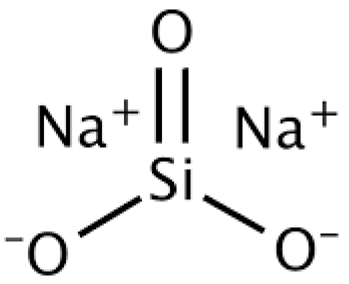
  Hydration

  Thermal energy – not required
- **Fly ash + GGBS**
  - Geopolymerisation+ Hydration
  - Thermal energy – not required

Molarity

- Concentration of alkaline solution
- NaOH = 40g/mol.
- 1 lithre of water +40g of NaOH = 1M
- For 12 M, 40x12=480g of NaOH in 1 l of water
- Ratio of NaOH/Na_2O SiO_2





Alkaline solution

- Tap water + Sodium hydroxide + sodium silicate ---→ Alakaline solution
- Produces heat upto 80 Degree Celsius
- Stir and cool it
- Use after 24 hours.

Precautions

- Highly alkaline + hot at early hours
- Not to touch with bare hand

- Use protective measures
- If it falls on skin -→ loss of skin
- Takes long time for healing
- Avoid falling of solution on skin, ear, eye etc

First Aid

- Immediately splash jet of water on affected area continuously
- Irritation stops in minutes
- If problem persists – Consult doctor
- Many researchers hide this info

Eyes

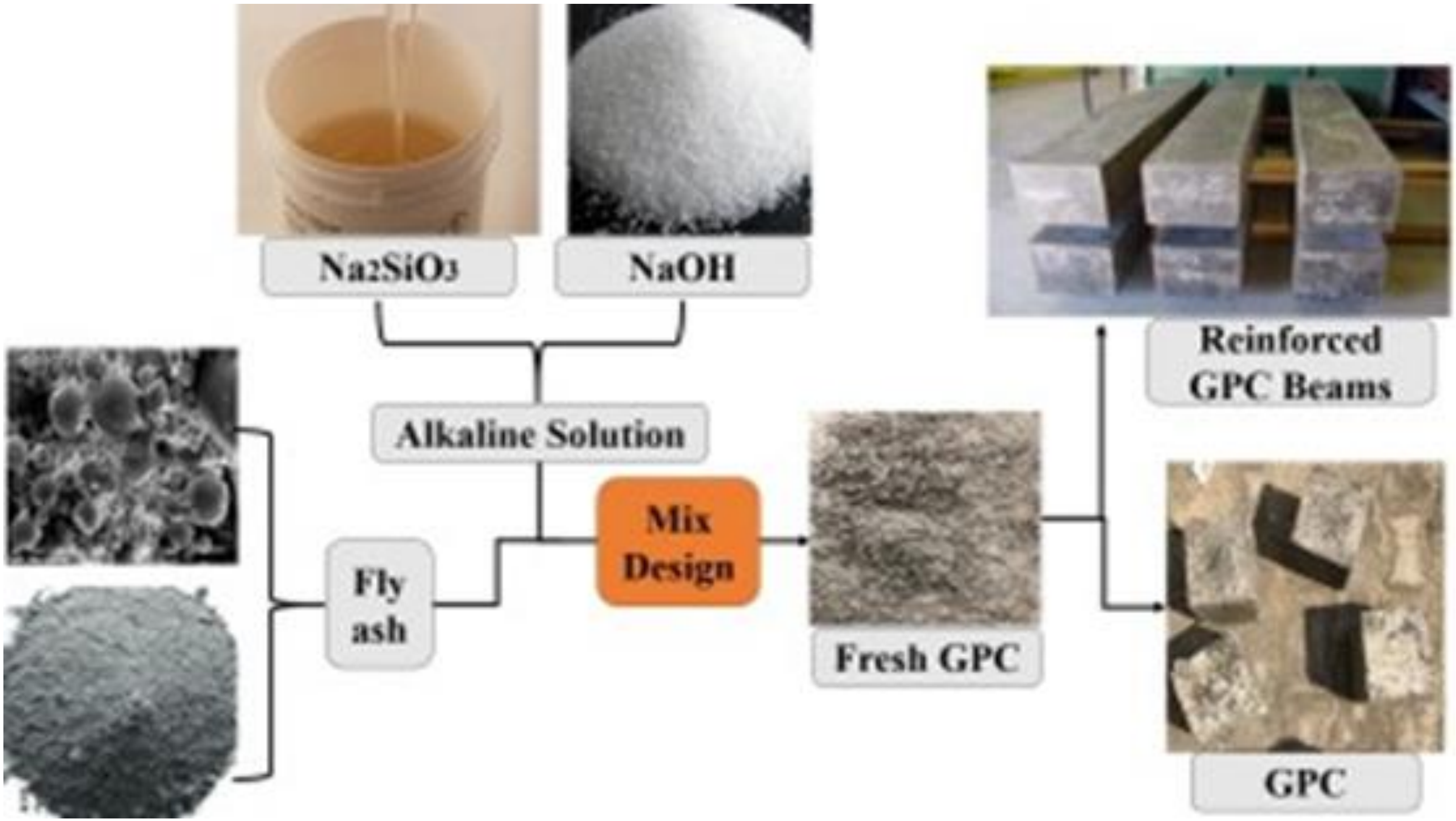
Immediately wash eyes with clear water
Consult doctor
Don’t delay
Steroids my be used as prescribed



Challenges

Quality of fly ash - May not be uniform
GGBS √
Sodium Hydroxide - Flakes
Sodium silicate – Solution
Solidification - Rock like
Trials are preferred

Geopolymers



Water – to – Cement ratio

- Water -→ Fluid
- Cement -→ Binder
- **W/C -→ Fluid/binder ratio**
- Ratio by weight
- Mortar (masonry unit) – 0.15 to 0.3
- Plastering Mortar – 0.9 – 1.1
- Concrete – 0.3 to 0.6

Forms of Geopolymers

+

Fine aggregate

=

Paste

Mortar

Concrete

Masonry

Geopolymer paste

Fly ash + GGBS+ Alkaline Solution

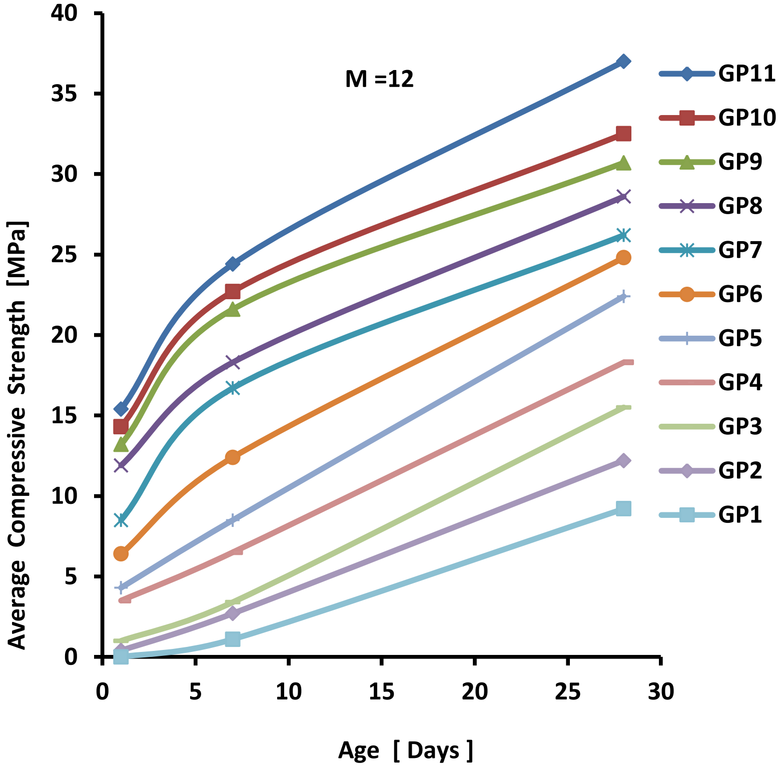
Studies on Geopolymer Paste

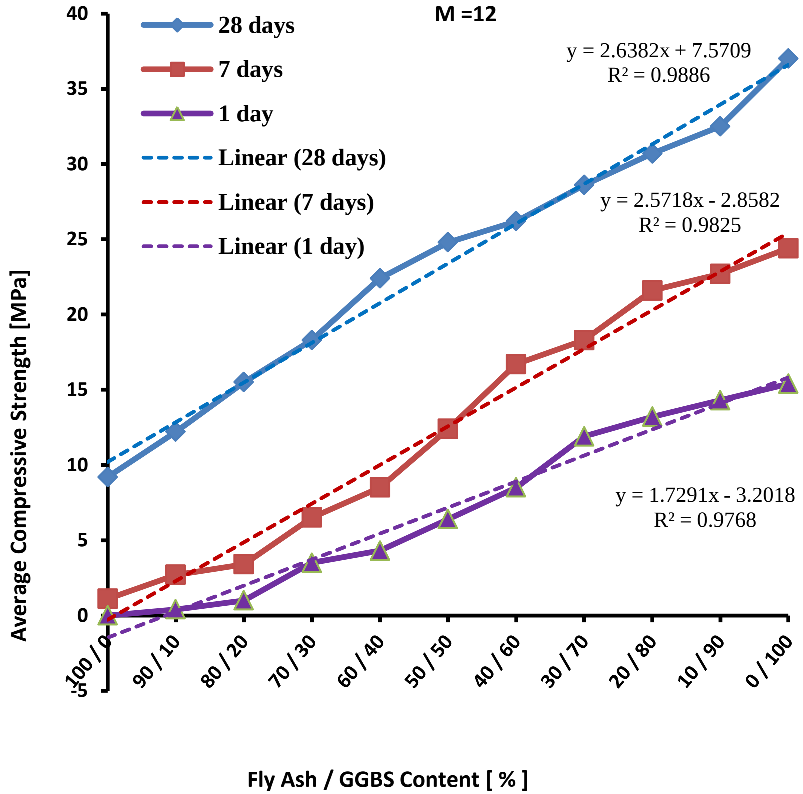
Alkaline fluid content – a constant function of respective normal consistency

Series Designation, Binder Composition and Molarity of NaOH for Geopolymer Paste Series.											
Series ID	GP1	GP2	GP3	GP4	GP5	GP6	GP7	GP8	GP9	GP10	GP11
[FA:GGBS] %	100:0	90:10	80:20	70:30	60:40	50:50	40:60	30:70	20:80	10:90	0:100
Molarity M of NaOH	12 for GP1 to GP11 and 6, 8, 10 and 12 for GP4										

Studies on Geopolymer Paste contd…

Compressive Strength



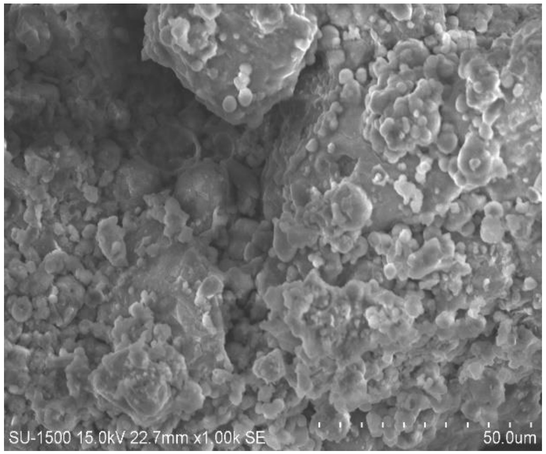


Variation of Comp. strength - with age and GGBS content

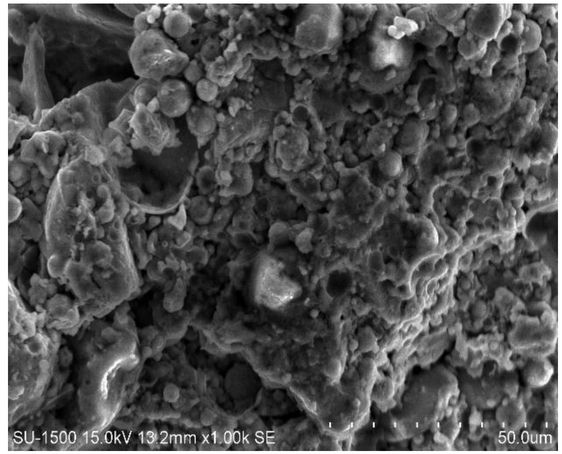
Studies on Geopolymer Paste   contd…

Evolution of micro-structure of GP paste GP4 **with age**

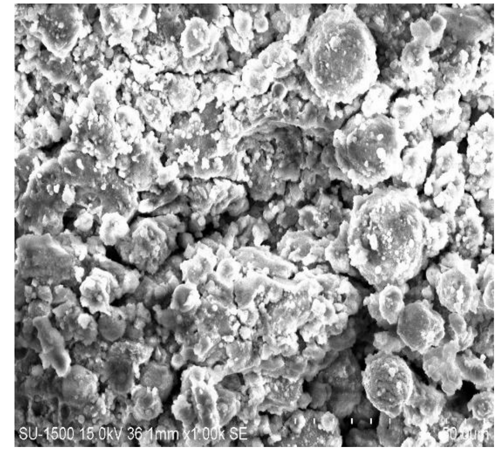
[fly ash to GGBS ratio of 70:30, 12M]



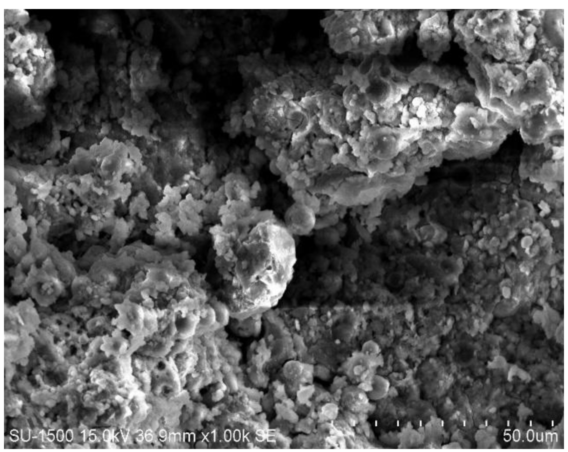
1 day   Strength: 2.9 MPa



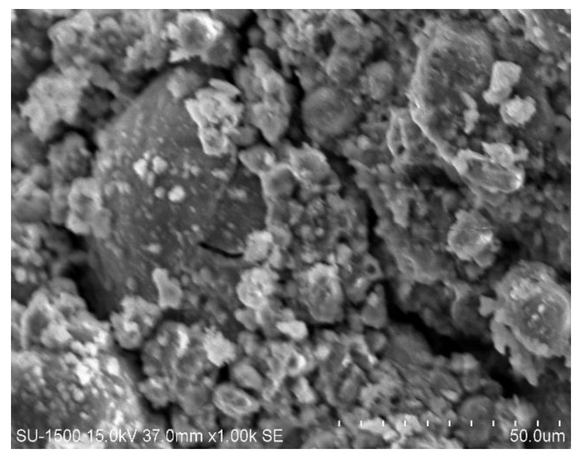
3 days   Strength: 3.3 MPa



7 days Strength: 6.4 MPa



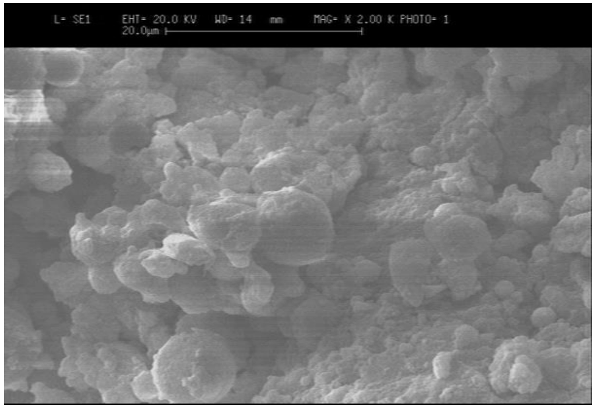
14 days   Strength: 14.2 MPa



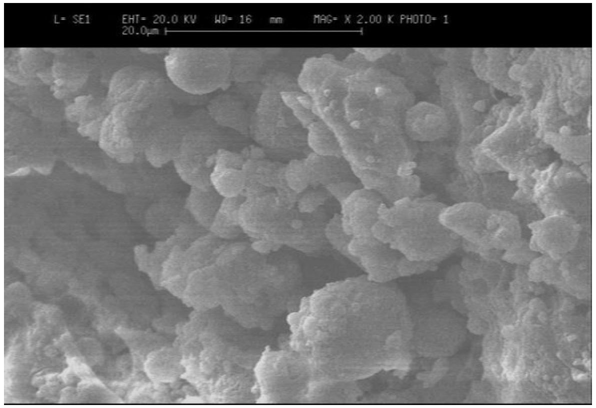
28 days   Strength: 20.4 MPa

Evolution of Micro structure with Molarity for GP4

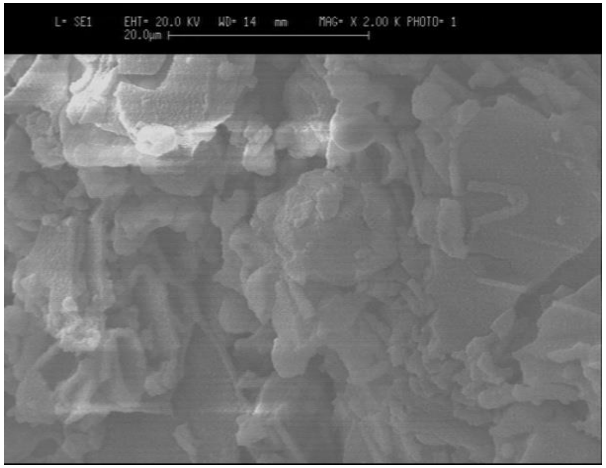
[fly ash to GGBS ratio of 70:30, 7 days]



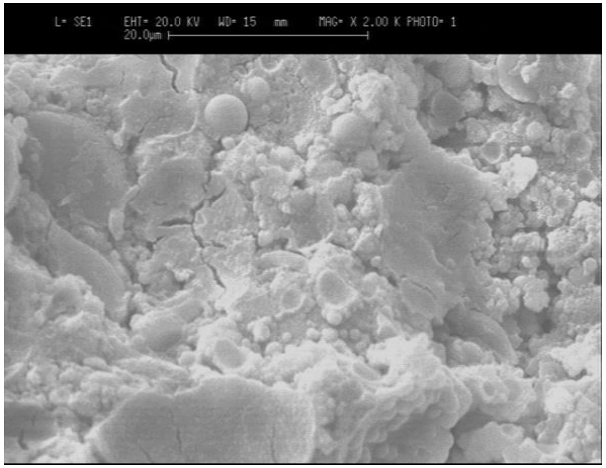
6M Strength: **2.6 MPa**



8M Strength: **4.8 MPa**



10M Strength: **5.4 MPa**



12M Strength: **6.5 MPa**

Findings on Paste

- Strength is more than OPC paste
- Setting Characteristics depends on many factors.
- Can be used for grouting – without curing

Geopolymer Mortar

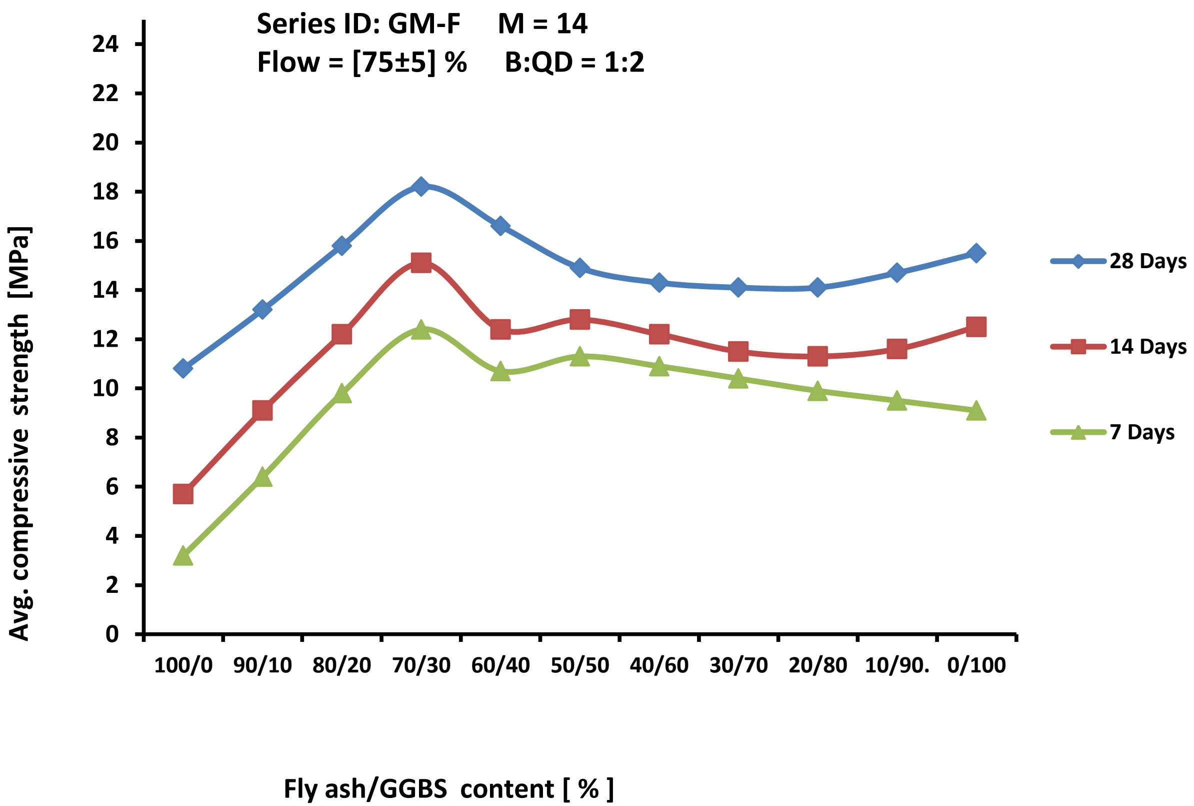
Studies on Geopolymer Mortar.

Mortar Composition and Series Designation of the GeopolymerMortar for different fluid-binder ratios and mortar proportion.

Fluid-to-Binder Ratio [F/B] = 0.35 for GM-A Series and 0.20 for GM-B Series Molarity [M] of Sodium Hydroxide : 14		
Binder Composition [Fly ash : GGBS] %	Series Designation	
	Mortar Proportion [Binder : Sand] 1 : 2.0	Mortar Proportion [Binder : QD] 1 : 1.5
100 : 00	GM-A1	GM-B1
90 : 10	GM-A2	GM-B2
80 : 20	GM-A3	GM-B3
70 : 30	GM-A4	GM-B4
60 : 40	GM-A5	GM-B5
50 : 50	GM-A6	GM-B6
40 : 60	GM-A7	GM-B7
30 : 70	GM-A8	GM-B8
20 : 80	GM-A9	GM-B9
10 : 90	GM-A10	GM-B10
00 : 100	GM-A11	GM-B11

Studies on Geopolymer Mortar. contd..

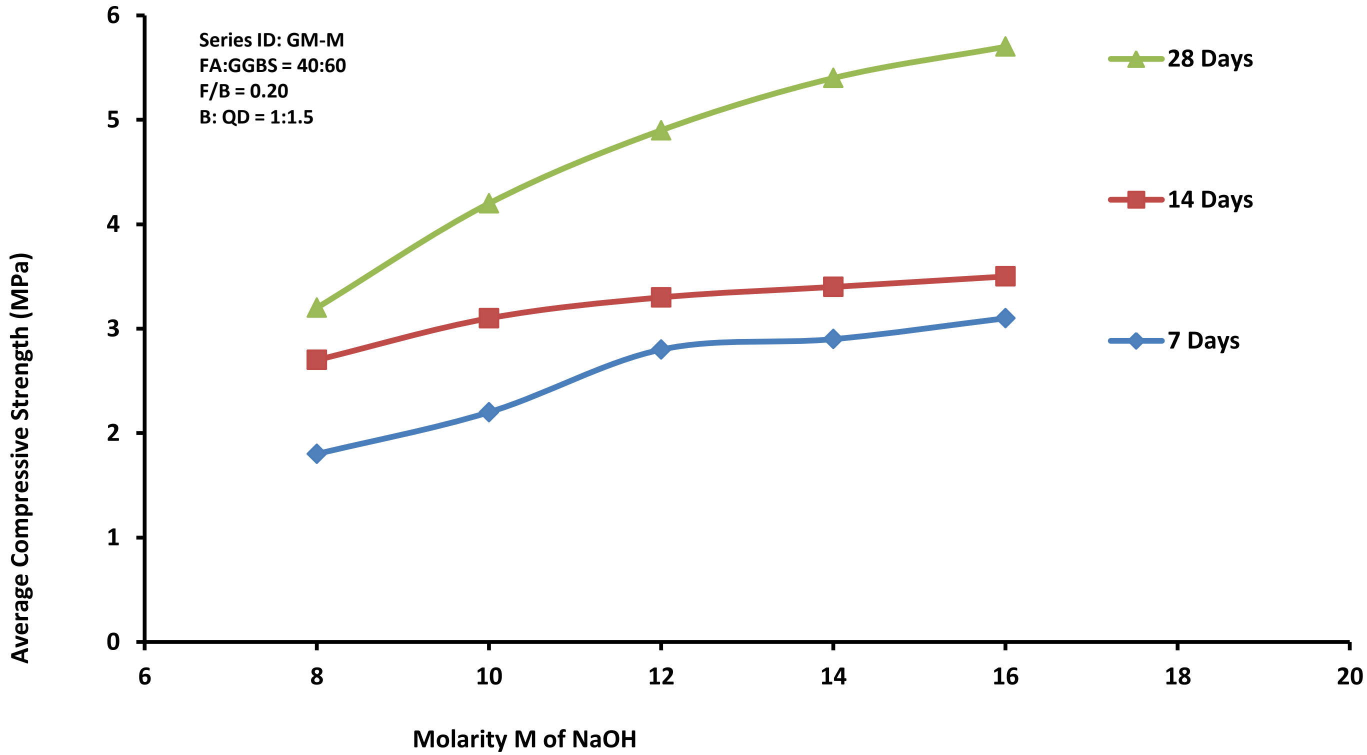
VARIATION OF STRENGTH WITH BINDER COMPOSITION AND AGE AT CONSTANT FLOW OF [75±5] %



Variation of strength w. r. t. fly ash-to-GGBS ratio for different ages at constant flow of [75±5] %.

Studies on Geopolymer Mortar. contd..

VARIATION OF STRENGTH WITH MOLARITY OF NaOH



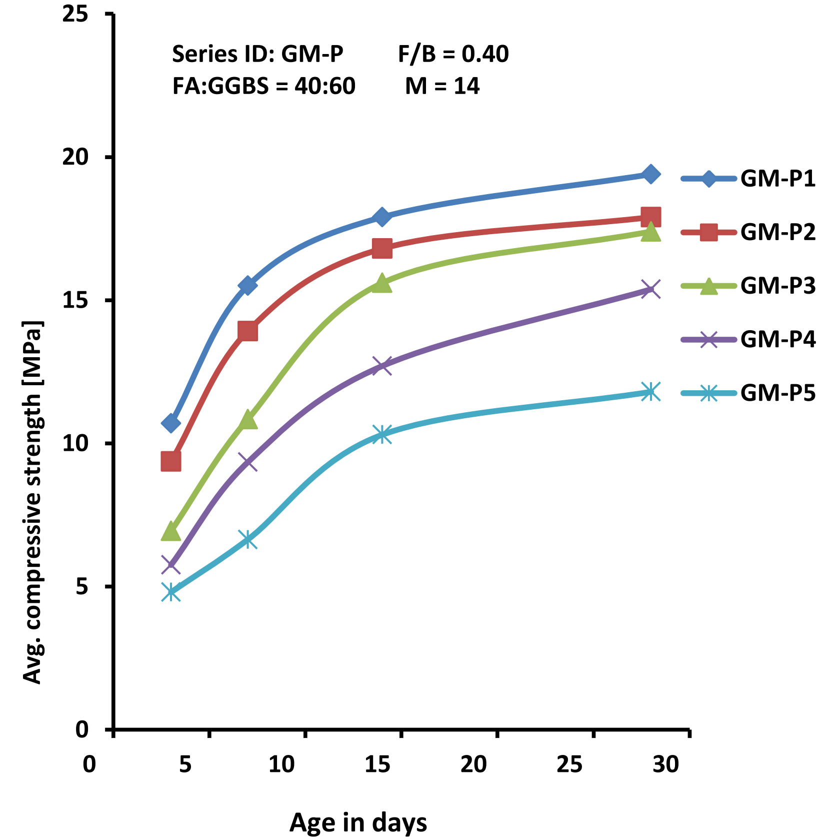
Variation of strength w. r. t. molarity of NaOH solution in the alkaline fluid, for different ages.

Studies on Geopolymer Mortar. contd..

VARIATION OF STRENGTH WITH MORTAR PROPORTION

Mortar Composition and the Series Designation of the GP Mortar for different Mortar Proportion.

[Fly ash : GGBS] % = 40 : 60	
Molarity [M] of NaOH : 14	
[F/B] = 0.40	
Mortar Proportion [Binder : QD]	**Series Designation**
1 : 1.0	**GM-P1**
1 : 1.5	**GM-P2**
1 : 2.0	**GM-P3**
1 : 2.5	**GM-P4**
1 : 3.0	**GM-P5**



Variation of strength w. r. t. age [14 M]

Geopolymer composites

Partially saturated	Fully Saturated
w/c ratio < 0.3	w/c > 0.3
Solids + Liquid + Air	Solid + Liquid
Mortar	Concrete
Suitable for making bricks/blocks	Suitable for structural material > 20 MPa
Requires compaction	May not require compaction

Geopolymer Blocks Considered

- **Manually made**
- **Hydraulic Press**

Curing Conditions

- ❑ **Heat cured (without water)**
- ❑ **Ambient (Without water)**

Materials mixed in dry condition

Alkaline fluid is added

Mixed to get homogeneous mix

Required quantity of mortar - weighed

Mridini Developed AT IISc for soil stabilized blocks

Presses using lever - manually

Mould is lubricated

Mould is filled with harsh mortar

Mould is pressed with cover plate manually

Fresh block is ejected

Weight of the block is noted

Neatly labeled

Cured in open air

Three Phase System

Mortar

↓

Solids + Liquids + Air

(Binder & Aggregates) + Fluid + Voids

Tested for Compression

Block with crack – After testing

Block making – Static and Vibro compaction

Mould is filled with mortar

The mould is covered

Compacted in hydraulic machine

Block is taken out

Cured in Open air

Mass production of the blocks

Blocks in open field

Pavers stacked

Blocks with different shape and size

PB1

PB2

PB3

CB1

CB2

CB3

Dimensions of the blocks

Sl no.	Block ID	Size (mm)
1	PB1	220 × 150 × 60 (outer to outer)
2	PB2	200 × 160 × 60 (outer to outer)
3	PB3	200 × 120 × 60 (outer to outer)
4	CB1	200 × 110 × 60
5	CB2	Cylinder, Dia = 38, Ht = 76
6	CB3	230 × 190 × 90

Ambient Cured Blocks

No thermal input

No traditional Curing

No Demoulding

Only compress and keep ready

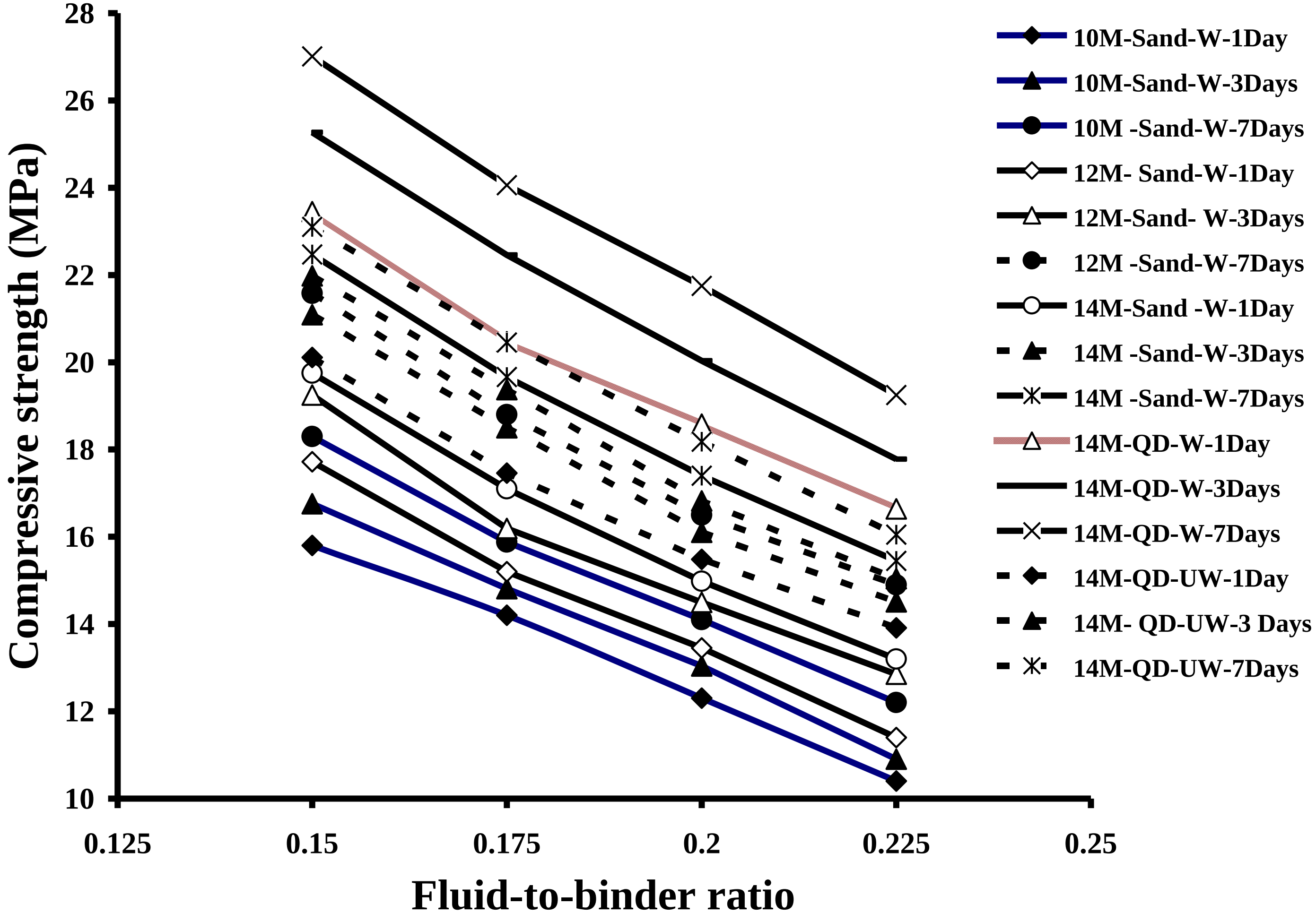
Heat Cured Geopolymer blocks

Geopolymer Masonry Blocks

- **Heat Cured – Oven @60^{O}C for 24 hours**

- **Ambient Cured – Open Air**

Strength Vs Fluid-to-binder ratio (Heat cured blocks)

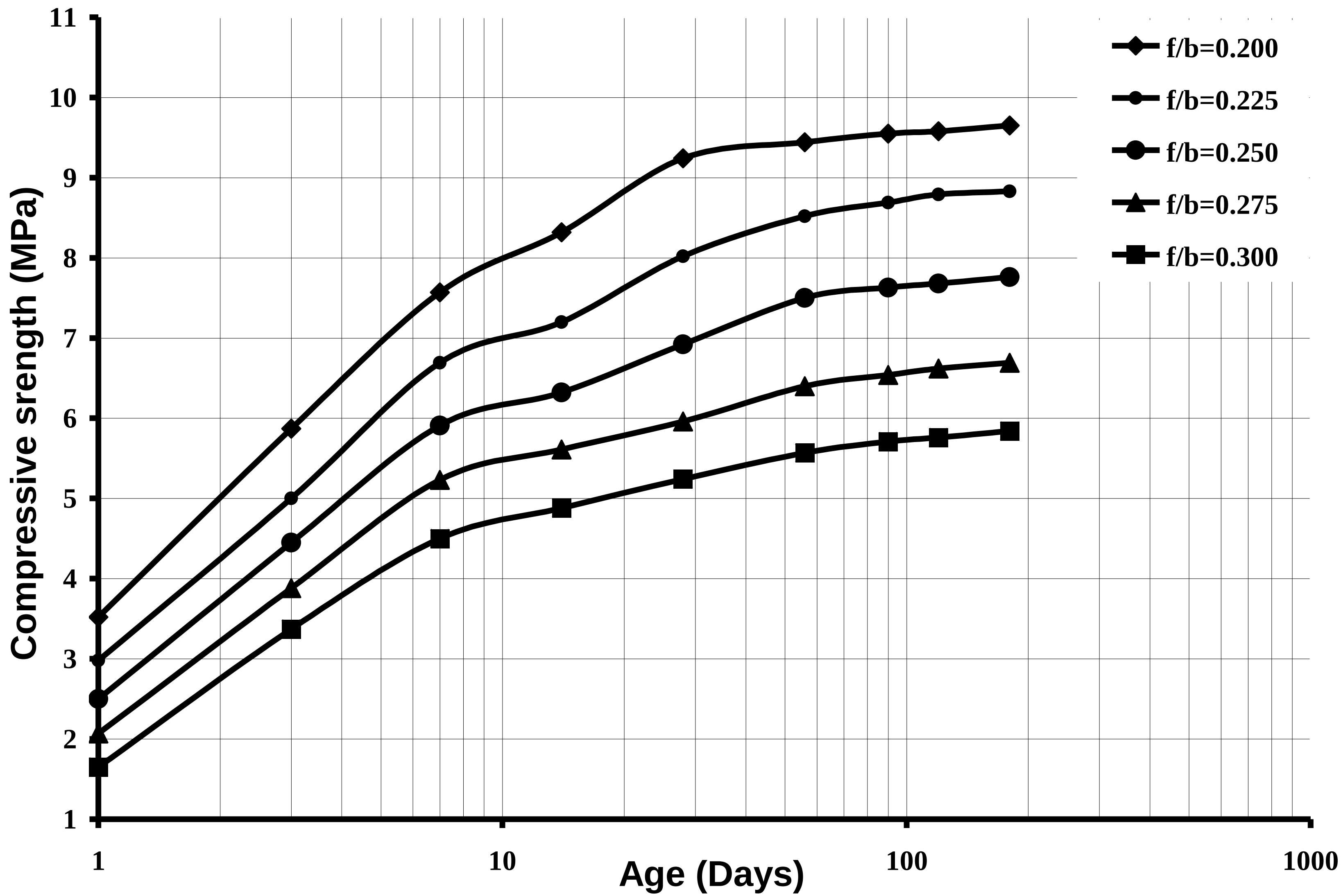


Ambient Cured Geopolymer Blocks

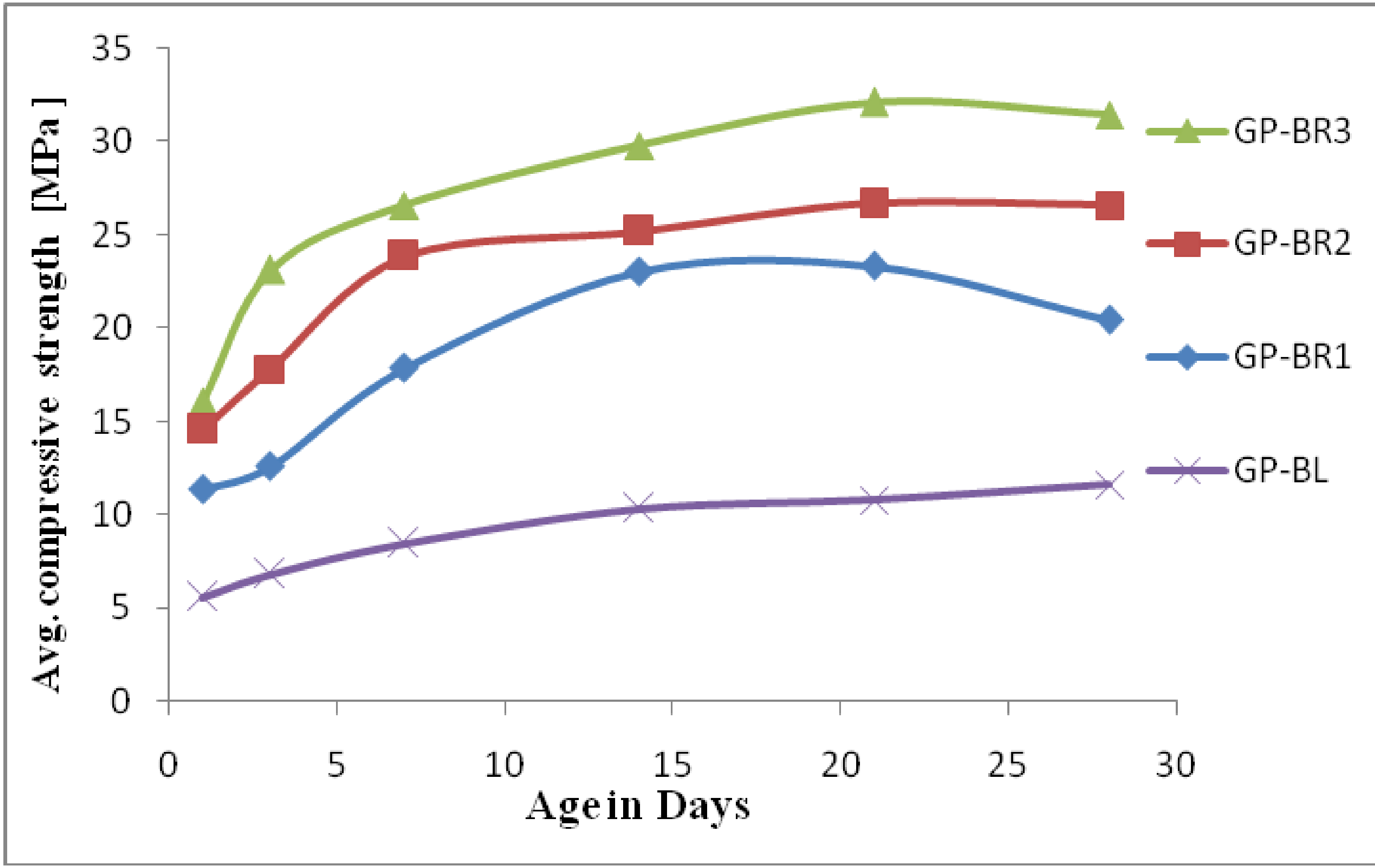
Parameters

- Age of the sample: 1, 3,7,14, 28, 56, 90, 120 and 180 days.
- Fly ash: FA1, FA2, FA3 and FA4.
- Alkaline activator: Sodium hydroxide and potassium hydroxide.
- Ratio of binder-to-aggregate: 1:1, 1:2 and 1:3.
- Degree of saturation: 40 and 60%.
- Molarity of alkaline solution: 8, 10, 12 and 14 M.
- Fine aggregate: Sand, quarry dust and pond ash.
- Temperature: 25, 30, 40, 50, 60, 70 and 80^{o}C.
- Binder: fly ash, GGBFS, silica fume, metakaolin.

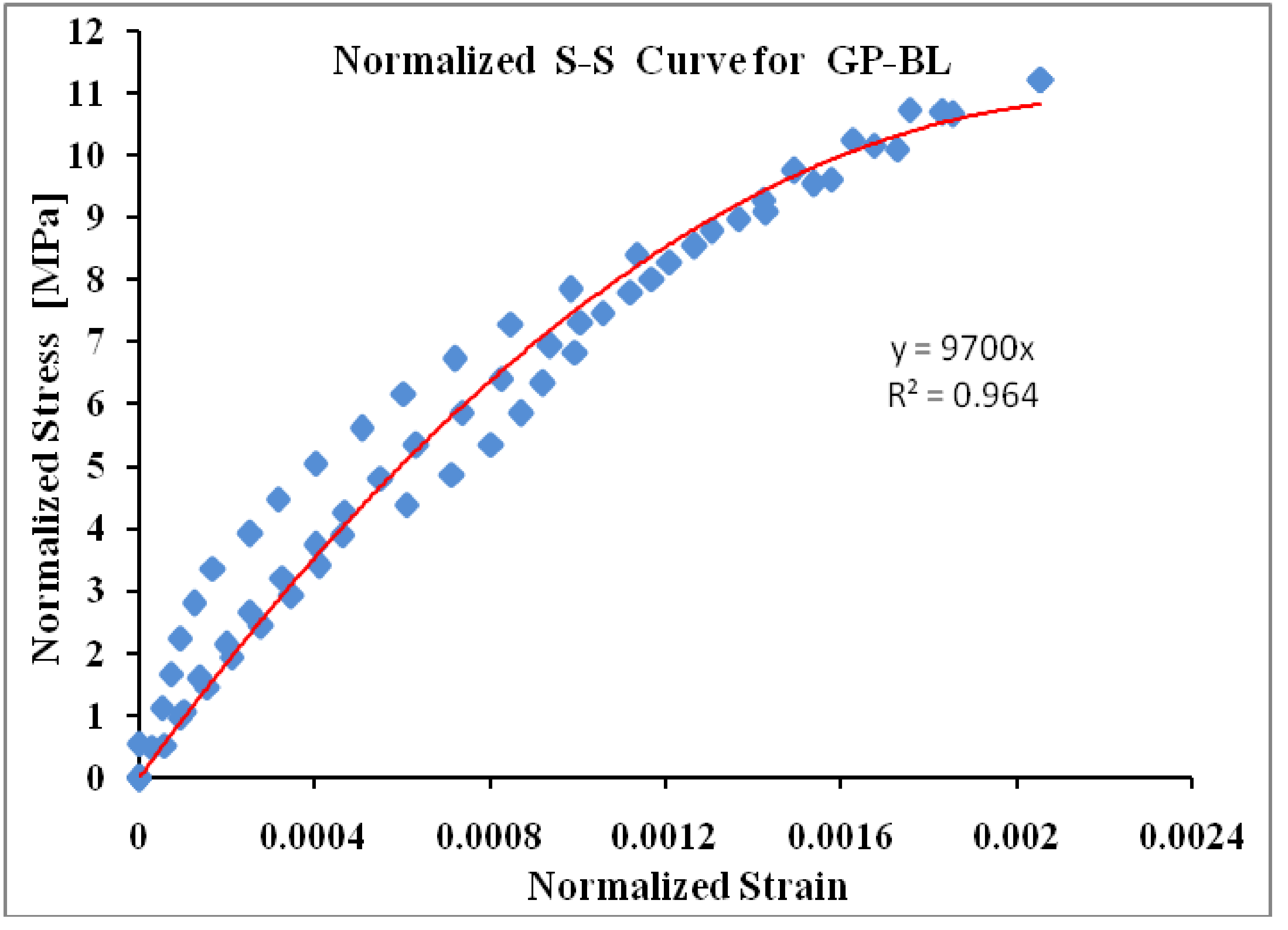
Strength Development with age - Geopolymer blocks



Strength Development with age



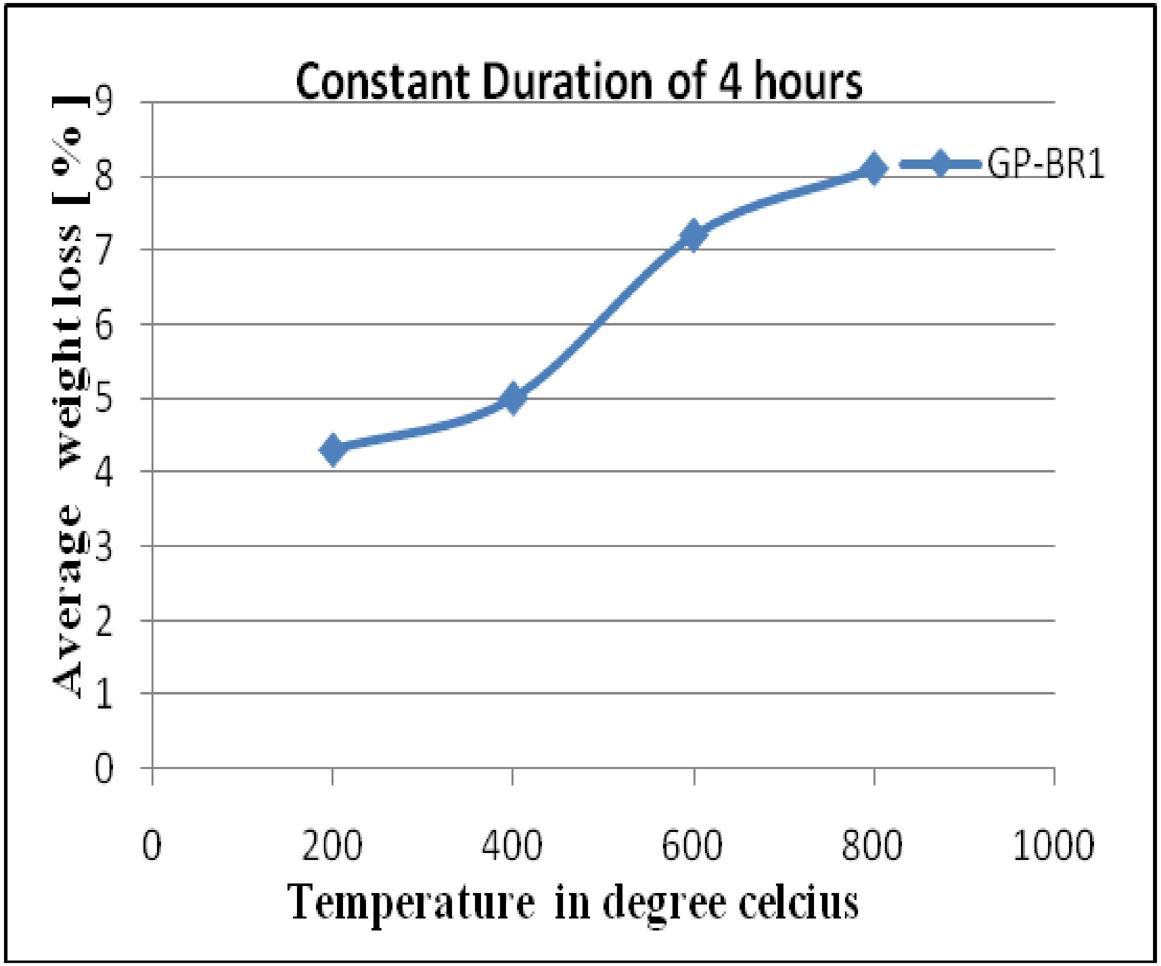
Typical Stress- Strain Curve



Modulus of Elasticity

Series Id.	Avg. ultimate compressive strength [MPa]	0.25 x Avg. ultimate strength (σ)[MPa]	Strain at stress level of 0.25 x avg. ult. Strength (ε)	Secant Modulus (σ /ε) [MPa]
BR1	26.93	6.73	0.000406	16582.5
BR2	20.00	5.00	0.000580	8620.7
BR3	25.20	6.30	0.000354	17806.7
BL	12.63	3.16	0.000352	8977.3

Weight loss with elevated temperature – 2 hours



Durability Tests on Blocks

Loss of mass and water content as per

ASTM: D559–2003

Loss of mass - 2.0 %

Water absorption - 2.4%

Geopolymer Blocks as masonry

Bricks
Solid blocks
Hollow blocks

Wallets

Geopolymer Brick Wallets

CASTING OF GEOPOLYMER BRICKS WALLETES

- Bricks- 8M NaOH bricks
- Mortar- 1:6 cement: River sand mortar of type M2 as per IS 1905-1987
- Bed & Head Joints - 10mm thick
- Wallete dimensions- (hxbxt) = 1105mm X 1165mm X 107mm.
- h/t ratio= 10.32

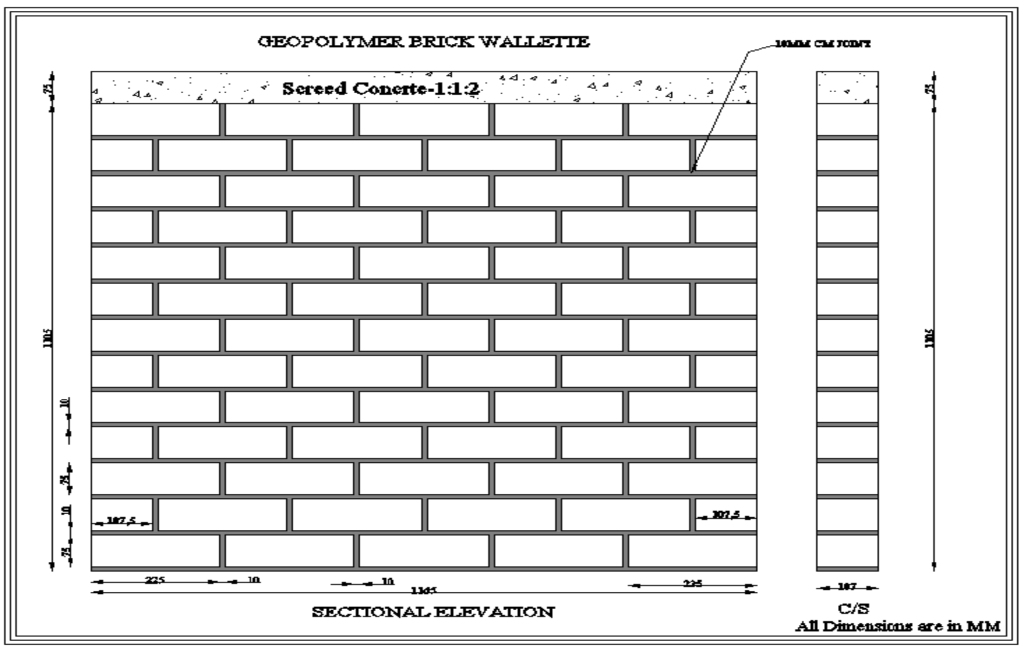


Fig : Schematic Representation of Typical geopolymer brick Wallete

Stretcher Bonded Geopolymer Brick Wallete kept for Curing

Geopolymer Brick Wallets

TESTING ARRANGEMENT OF GEOPOLYMER BRICKS WALLETES

Fig: Ladder Arrangement for Geopolymer brick Wallete

Fig: Ladder Arrangement for Eccentric Loading

- Loading assemblage was placed on the centre of bearing area of brick wallete.
- For eccentric loading-18mm from the centre of bearing surface of the wallete.

Geopolymer Solid Block Wallets

FAILURE PATTERN FOR THE GEOPOLYMER SOLID BLOCK WALLETE

Failure Pattern of Axially Loaded Wallete

Eccentrically Loaded Wallete

- Vertical cracks developed from top.
- Propagated till one third of the height from top.
- Spalling of cement joints at face of wallete.

Geopolymer Hollow Block Wallets

TESTING ARRANGEMENT OF GEOPOLYMER HOLLOW BLOCK WALLETES

Fig: Ladder Arrangement for Axially & Eccentrically Loaded Geopolymer Hollow Block Wallete

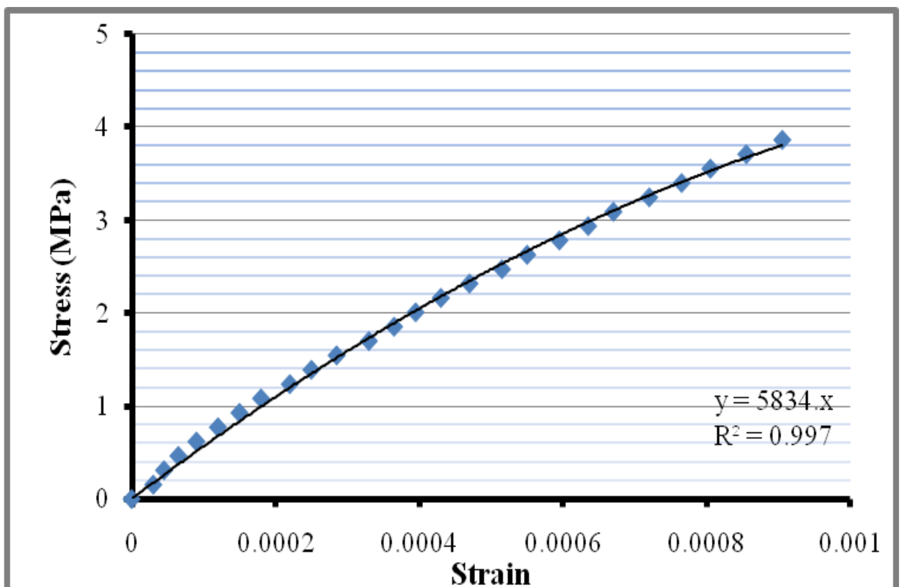
- Eccentricity 25 mm from the centre of bearing surface of the wallete.

Geopolymer Hollow Block Wallets

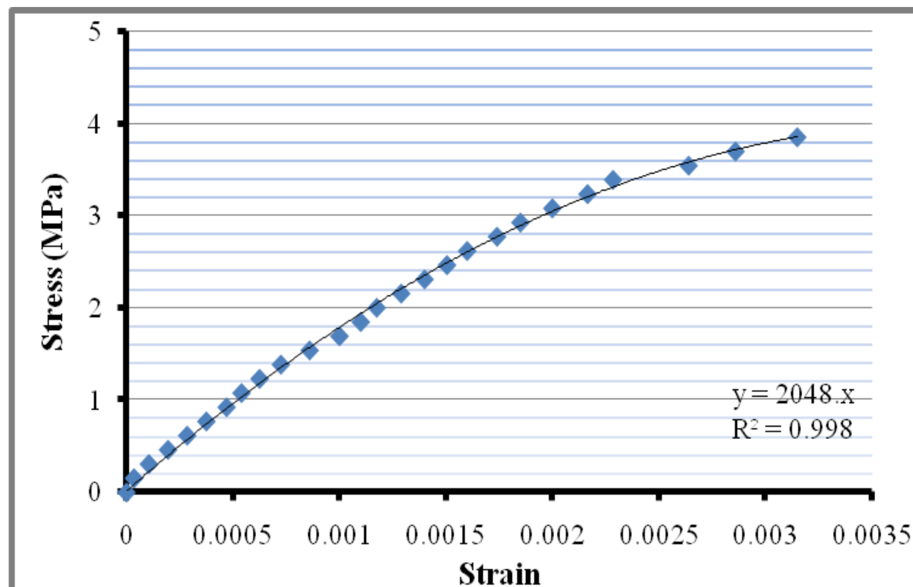
Table 23: RESULTS OF STRETCHER BONDED GEOPOLYMER HOLLOW BLOCK WALLETE

Type of loading	Wallete No	Load at first crack (KN)	Ultimate load (KN)	Compressive strength (MPa)	Avg. Compressive strength (MPa)
Axial loading	1	300	425	2.27	**2.31**
	2	380	442	2.36	
Eccentric loading	1	270	375	2.01	**1.95**
	2	245	355	1.89	

- Strength of Eccentrically loaded block wallets is 84% of Axially loaded wallets.



Normalized Stress-Strain curve for Axially Loaded Wallete



Normalized Stress-Strain curve for Eccentrically Loaded Wallete

Pictures of Masonry Structure in Field

Application of Geopolymer Masonry Units

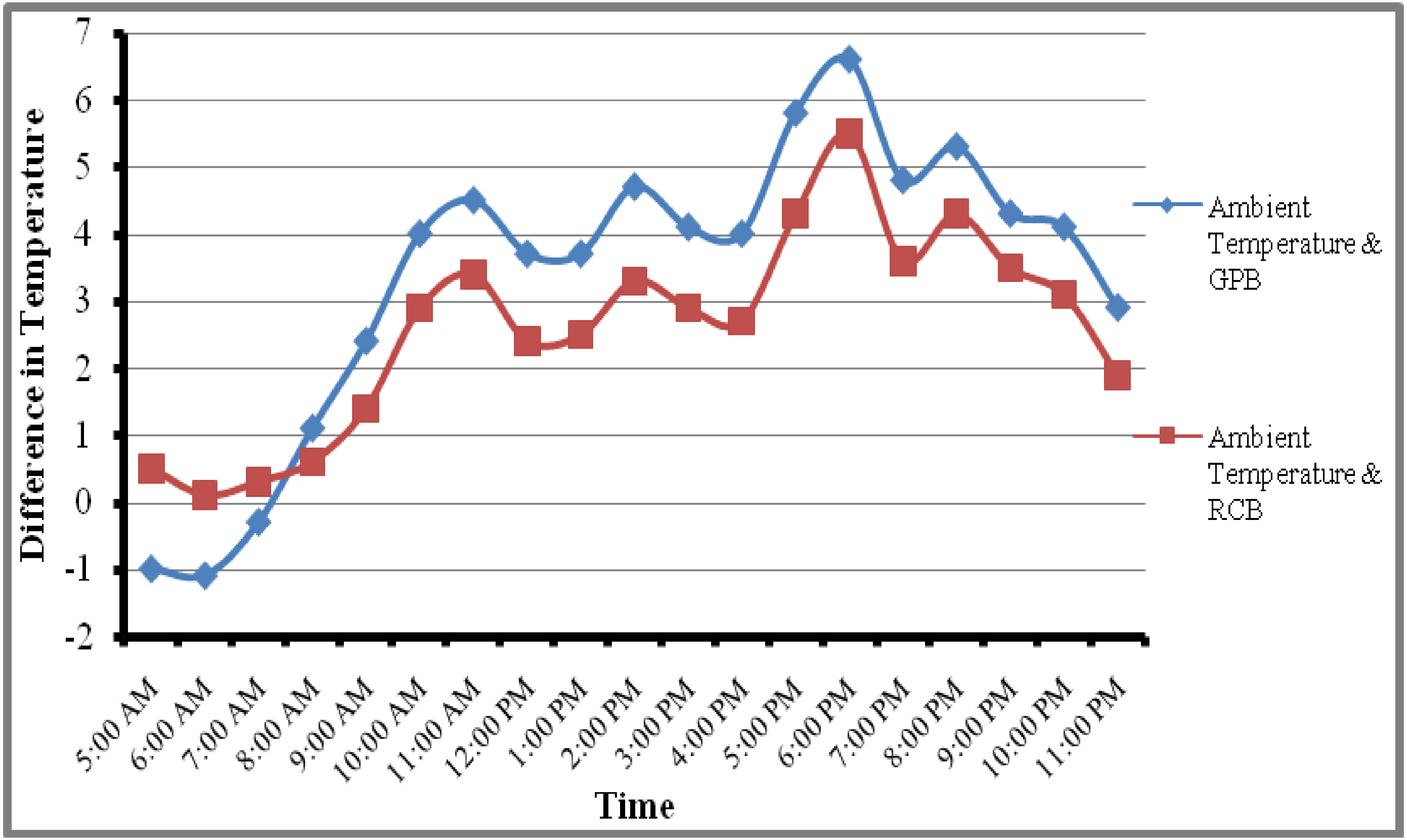
During Construction

Geopolymer Model House

OBSERVATION MADE

- No change in dimensions bricks and the walls.
- Brick edges remain sharp.
- **No erosion.**
- **No pitting.**
- **Less water absorptions.**
- **No distress.**
- Even after two years there was no sign of any deterioration of the walls of the geopolymer brick model house.
- The roof slab is casted after 24 months.

Thermal Comfort during winter



Geopolymer Concrete

Studies on Geopolymer Concrete

Parameters Considered: For GPC(GC)

Concrete Proportion [Binder : QD : CA] 1 : 2.0: 3.0		
Sodium Silicate : Sodium Hydroxide :: 2 : 1		
Molarity [M] of Sodium Hydroxide : 10		
Slump : (100±10) mm.		
Series Designation	Binder Composition [Fly ash : GGBS] %	F/B ratio
GC 1	100 : 00	0.65
GC 2	80 : 20	0.65
GC 3	60 : 40	0.70
GC 4	40 : 60	0.75
GC 5	20 : 80	0.75
GC 6	00 : 100	0.75

For Reference Concrete (NC) Concrete Proportion [OPC: QD : CA] 1 : 2.0: 3.0

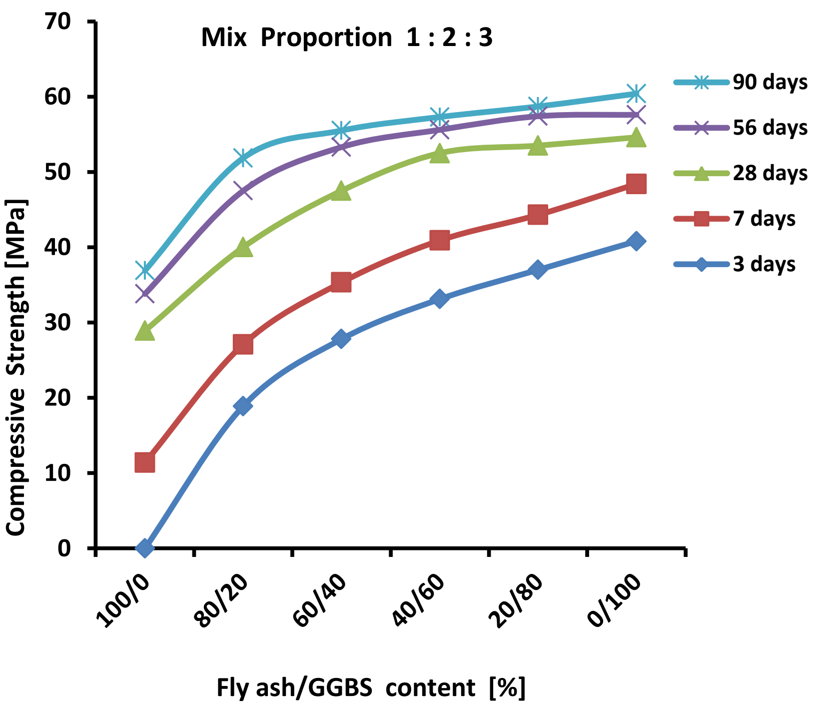
Slump : **(100±10) mm** **W/C = 0.6**

Studies on Geopolymer Concrete. contd..

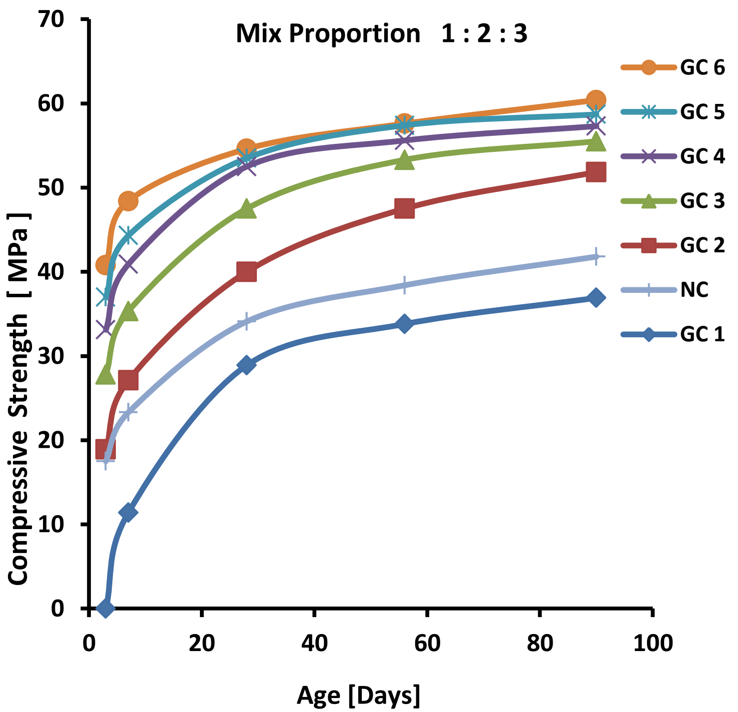
MASS DENSITY: For GC, 2424-2516 kg/cum

For NC, 2504-2550 kg/cum

COMPRESSIVE STRENGTH:



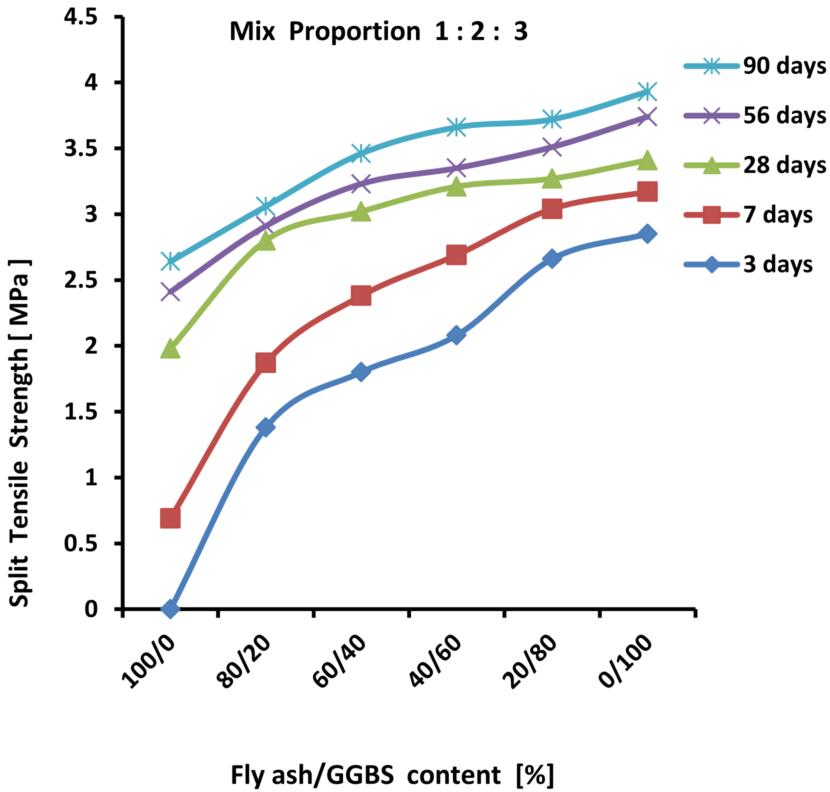
Variation w. r. t. fly ash-GGBS



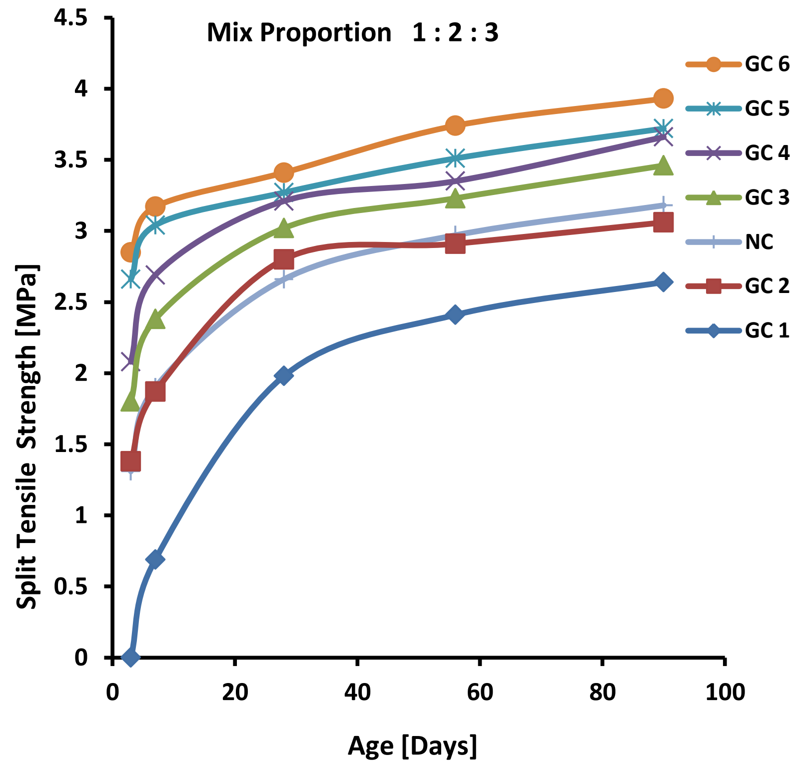
Variation w. r. t. age.

Studies on Geopolymer Concrete. contd..

SPLIT TENSILE STRENGTH:



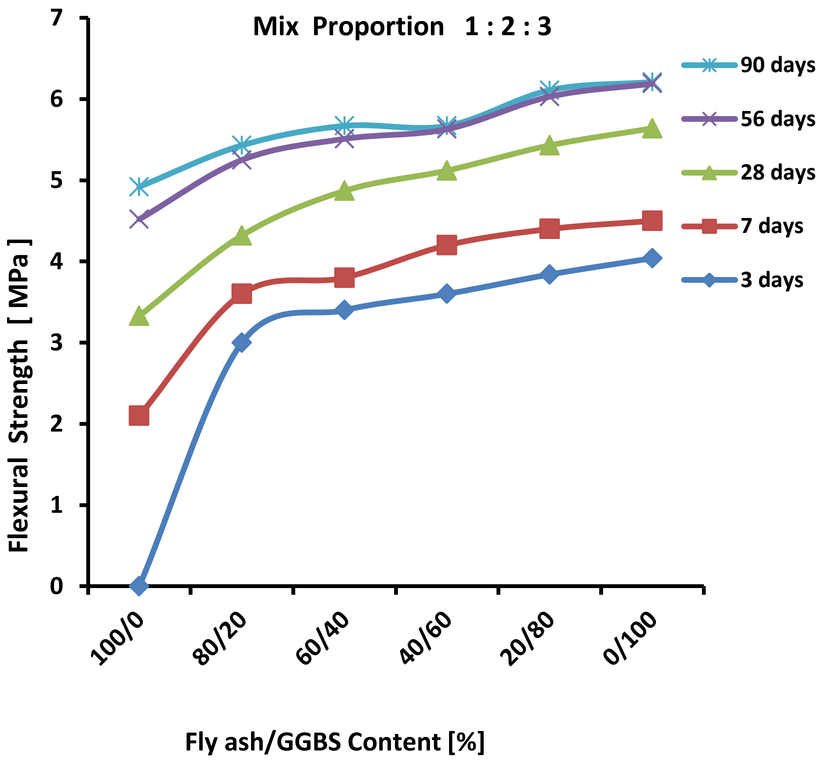
Variation w. r. t. fly ash-GGBS

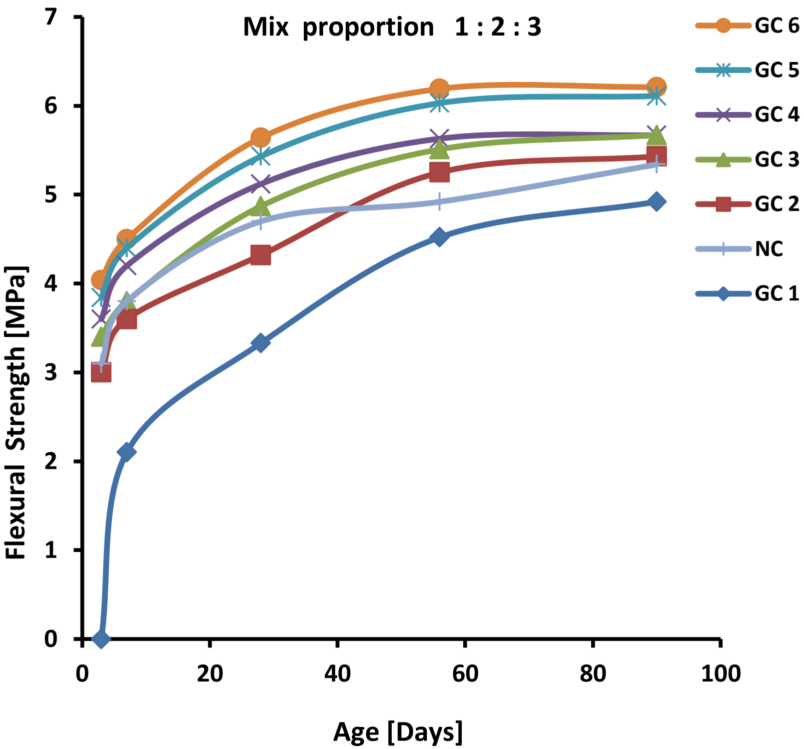


Variation w. r. t. age.

Studies on Geopolymer Concrete. contd..

FLEXURAL STRENGTH:

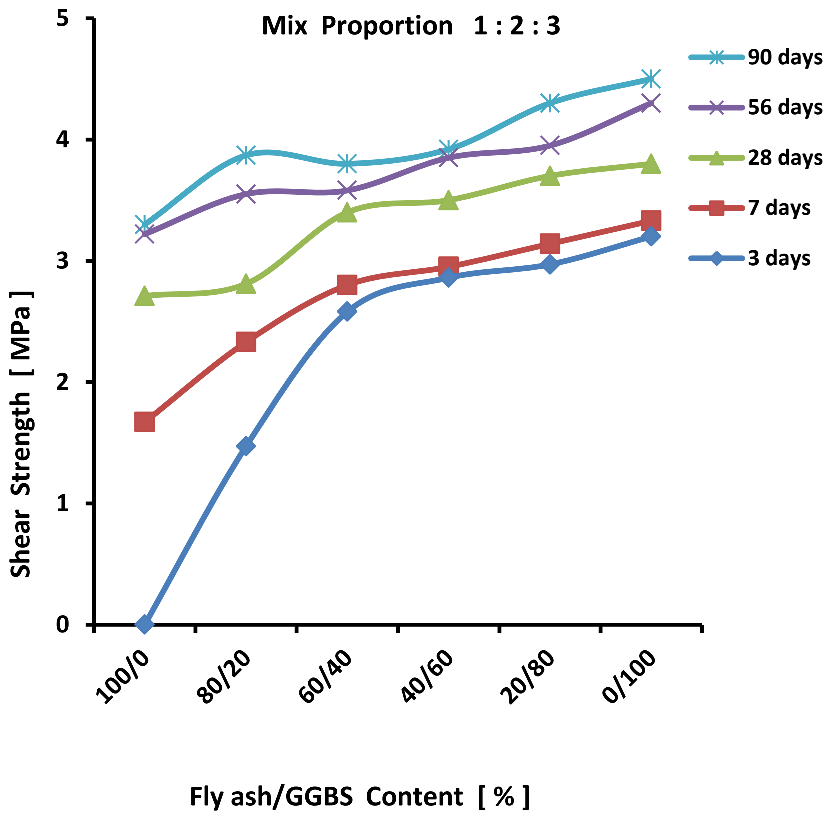


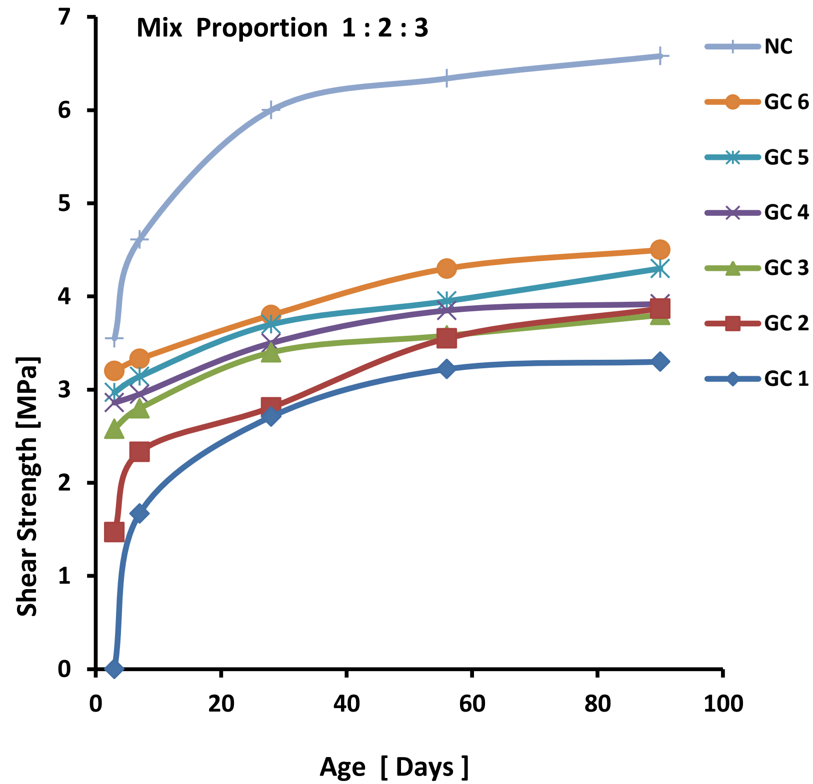


Studies on Geopolymer Concrete. contd..

SHEAR STRENGTH:

{Bairagi and Modhera **[134]** and Baruah and Talukdar **[135]**}





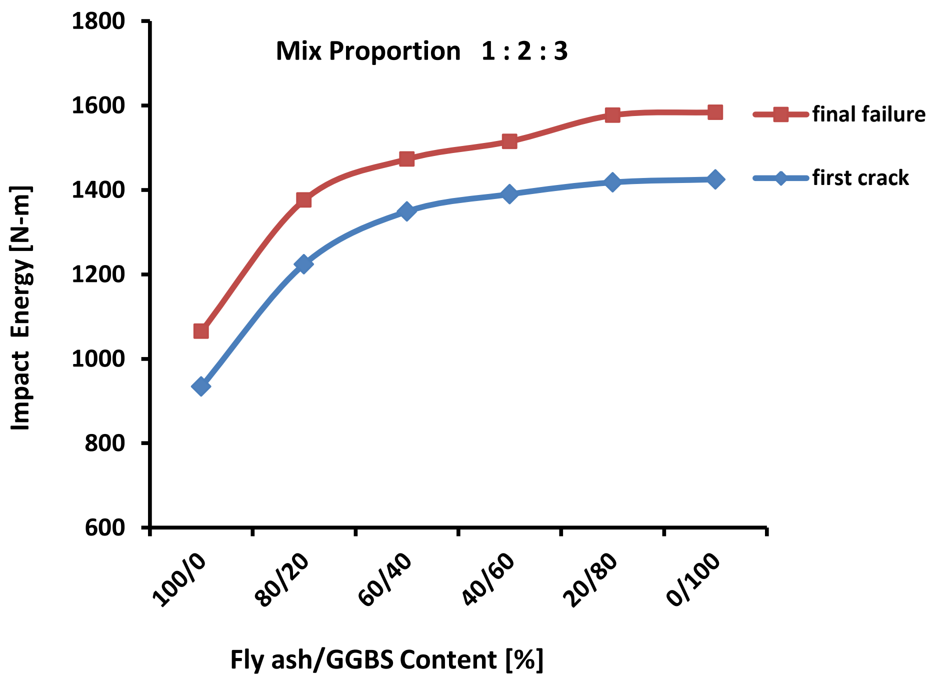
Studies on Geopolymer Concrete. contd..

IMPACT STRENGTH: [Schruder's Impact Testing]

Specimen Size =150mm dia. and 60 mm thick

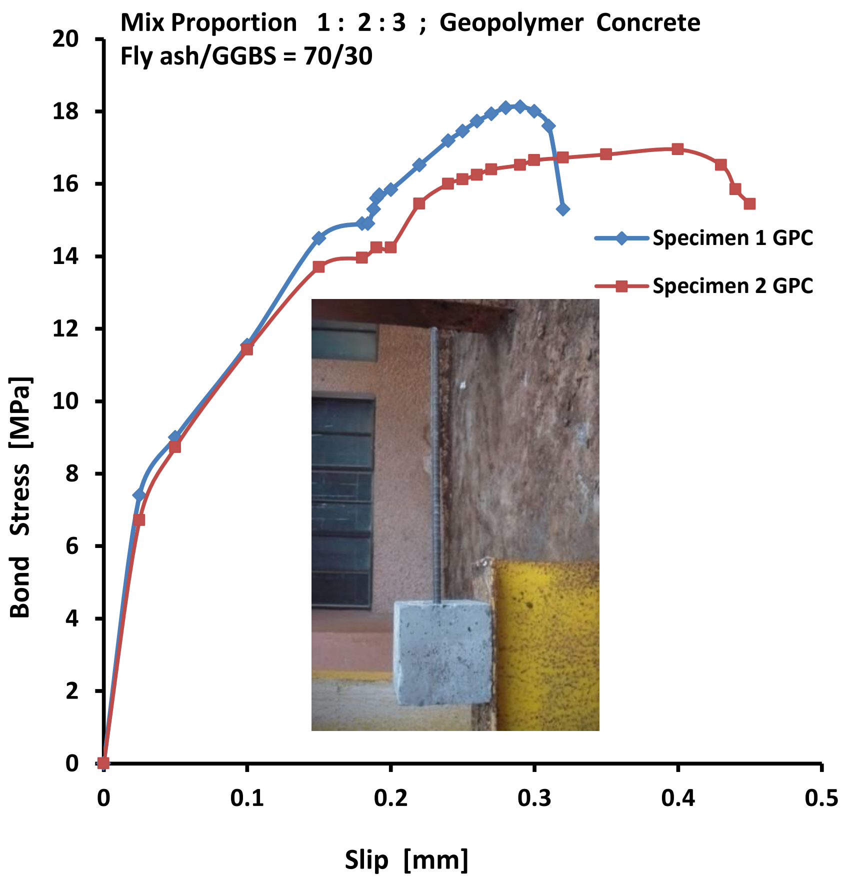
Impact Energy = w.h.n

w = 45.4 N, h = 0.457 m., n = No. of blows to cause the failure.

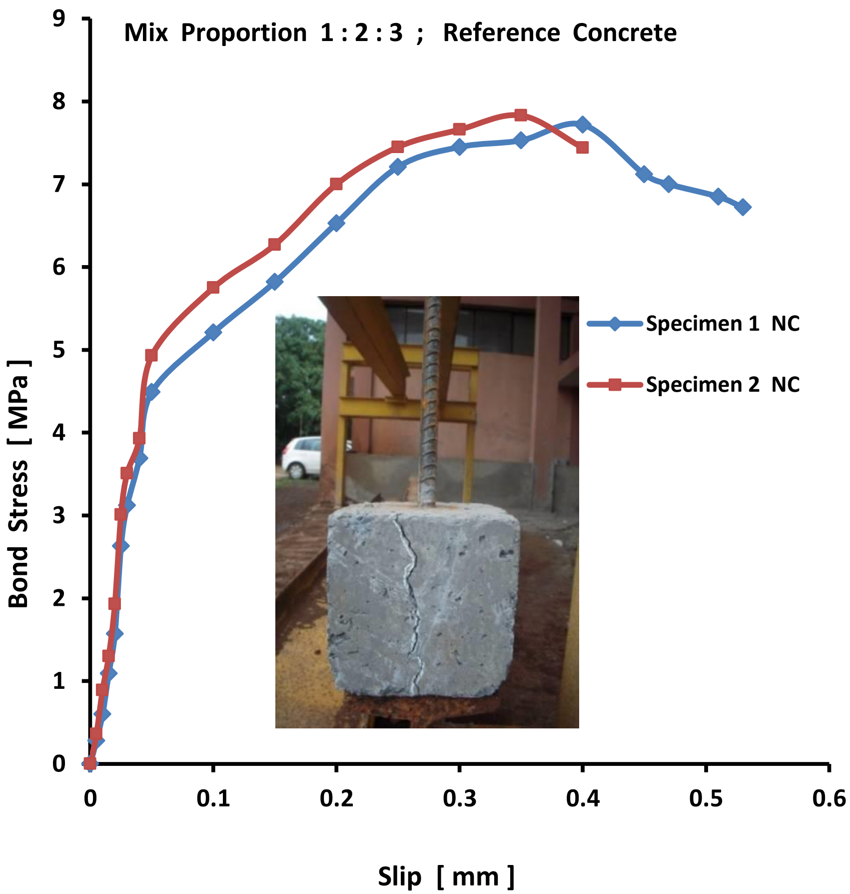


Studies on Geopolymer Concrete. contd..

PULL-OUT STRENGTH

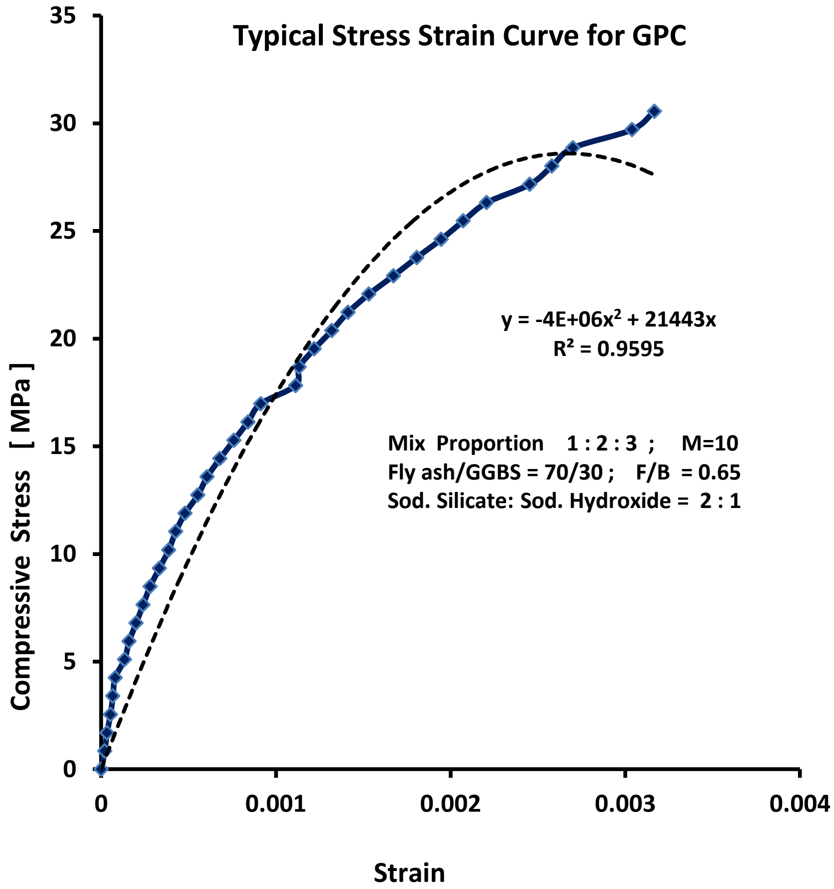


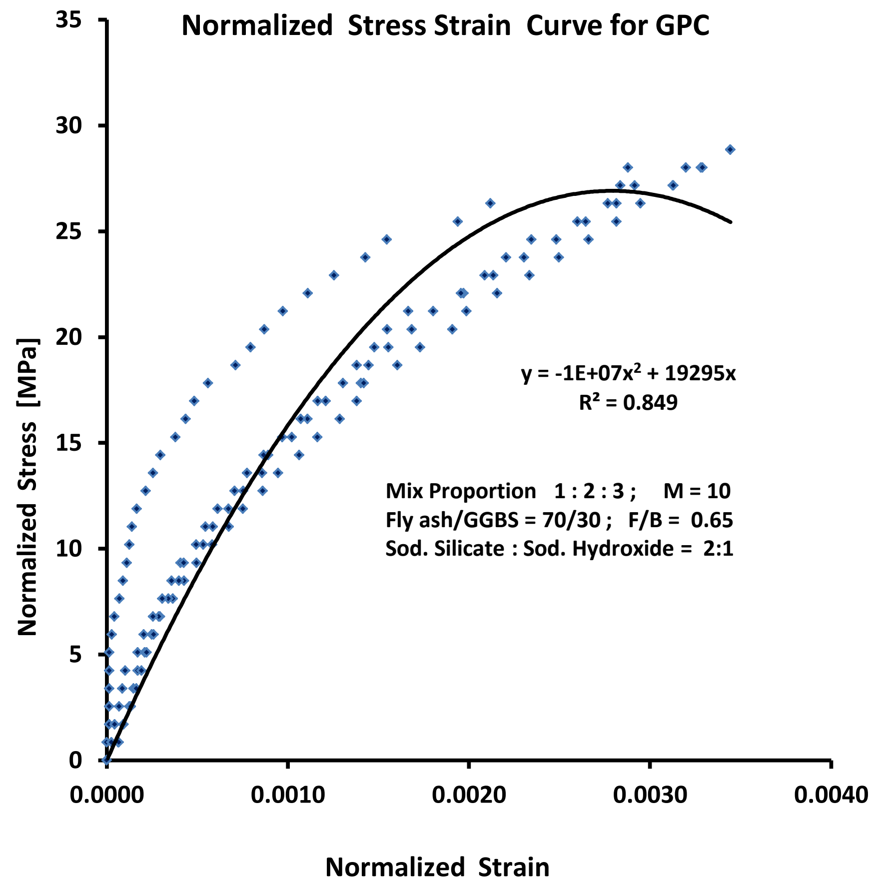
Bond stress v/s relative bar slip for GP Concrete



Bond stress v/s relative bar slip for Ref. Concrete

Studies on Geopolymer Concrete. contd..





Typical S-S curve for GP concrete

Ult.(cylinder) compr. strength: 31.1 MPa

Normalized S-S curve for GP concrete

Avg. ult.(cylinder) compr. strength: 32.53 MPa

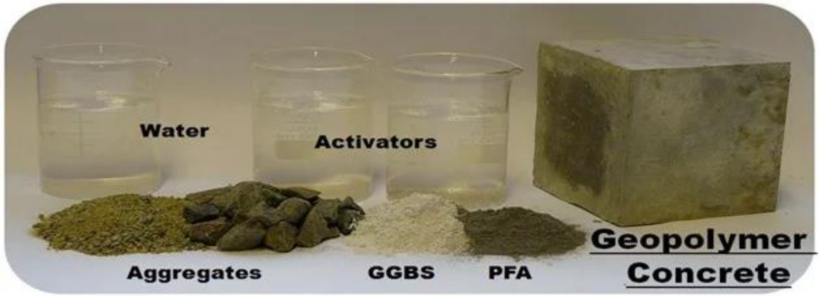
Comparison

Conventional

- Strength – Hydration
- Cement is binder
- Water/Stream curing
- Water is used for mixing
- Definite procedure for mix design

Geopolymer

- Strength – Geopolymerisation +hydration
- Fly ash, GGBS….. Are binders
- Thermal curing – if only fly ash
- Alkaline solution is sued
- Developing stage



Concluding Remarks

- Geopolymers can be developed in line with Portland cement products
- High compressive strength, Durable
- Used for special applications
  - Precast industry
  - Fast grouting
  - High early strength masonry units
  - Lining of furnace

Concluding Remarks

Geopolymer Concrete Satisfy

- Slump
- Compressive Strength
- Split tensile Strength
- Flexural Strength
- Impact Strength
- Shear Strength

With out OPC and Curing

THANK YOU

For any questions:

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