Development of Geopolymer cements/concretes in India

SRM
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[Under section 3 of UGC Act 1956]

Geopolymer Concretes - Indian Context.

N P Rajamane PhD
Head
Centre for Advanced Concrete Research (CACR)

Dr. R Jeyalakshmi
Head, Dept of Chemistry

SRM University, Chennai, INDIA

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[Under section 3 of UGC Act 1956]

SRM UNIVERSITY
INDIA

CAMPUSES:

SOUTH INIDA :
KATTANKULATHUR CAMPUS &

CHENNAI CITY

NORTH INDIA:

DELHI & SIKKIM

Development of Geopolymer cements/concretes in India

The Geopolymer Camp 2015

organised by

Geopolymer Institute
INSSET, Université de Picardie,
48 rue Raspail,
02100 Saint-Quentin, France

Rajamane N.P., M.C. Nataraja and R. Jeyalakshmi

"Pozzolanic industrial waste based geopolymer concretes with low carbon footprint"

The Indian Concrete Journal, Vol. 88, No 7, July 2014, pp 49-68 Special Issue on Future Cements,

(Invited paper)

EXTERNALLY FUNDED RESEARCH AND DEVELOPMENT PROJECTS

- **Development of high temperature resistant Geopolymeric Composites Geopolymer Concretes.**
- **Development of Geopolymeric products for housing applications.**
- **Evaluation studies of corrosion resistant cements.**

Facilities

- Concrete Testing and Chemical Analysis equipment
- X-ray diffractometer
- FESEM, NMR, Impedence spectroscopy, etc
- Electrochemical workstation
- TGA/DSC
- Tubular furnace
- Thermal conductivity meter
- Dilatometer
- ATT-FTIR/UV-Vis-NIR
- RCPT
- Electric Resistivity

Thrust Areas

- Development of precast products:
  - ✓ Structural elements:
  - ✓ Beams, columns
  - ✓ Wall panel , pavers, building blocks (hollow and solid) :{normal and lightweight}
  - ✓ Road
  - ✓ Joins in pre cast elements.
- Development of thin members
  - ✓ Ferrocement slabs.
  - ➢ Reinforced by steel : RCC

GEOPOLYMER: PORTLAND CEMENT FREE BINDER SYSTEM FROM INDUSTRIAL WASTES

GEOPOLYMER - A NEW BINDER

Prof Davidovits of France

- Developed in mid 1970's
- Binding action by Aluminosilicate gel
- Utilised silica & alumina of specially processed clay (metakaolin) to get inorganic polymer of alumino-silicates

GEOPOLYMER - A NEW BINDER

Rangan and Hardijto, [2005]

- Activated SiO_2 & Al_2O_3 of fly ash
- Produced 3-D polymeric chain & ring structure consisting of Si-O-Al-O bonds of geopolymer
- Binder for structural grade concretes

MAJOR INGREDIENTS OF GEOPOLYMER CONCRETES

- **Geopolymeric Source Material**
- **Alkaline activators made of**
- **Filler System**

- **etc**

MAJOR INGREDIENTS OF GEOPOLYMER CONCRETES

- **Geopolymeric Source Materials**
  - ✓ Fly Ash
  - ✓ GGBS
  - ✓ Rice Husk Ash
  - ✓ Silica Fume
  - ✓ Metakaolin

MAJOR INGREDIENTS OF GEOPOLYMER CONCRETES

- **Alkaline activators made of**
  - ✓ **Alkali Hydroxide solutions**
  - ✓ **Alkali Silicate solutions**
- **etc**

MAJOR INGREDIENTS OF GEOPOLYMER CONCRETES

- **Filler System**
  - ✓ **River sand**
  - ✓ **Copper slag**
  - ✓ **Quartz sand**
  - ✓ **Crushed stone aggregates**
  - ✓ **Fly ash aggregates**
- **etc**

Alkaline Activator Solution

- **Mixture of NaOH solution and Sodium Silicate Solution**
- **Sodium Silicate Solution (SSS)**

Specific Gravity	**1.56-1.66**
Na_2O (%)	**15.5-16.5**
SiO_2 (%)	**31-33**
Weight ratio	**2**
Molar ratio	**2.05**
Iron content, ppm	**<100**
Baume	**51-55**

Geopolymer directly as binder

Geopolymer concretes

- 28 day compressive strengths >70 MPa
- Rational application of Particle Packing Theory, Strengths > 150 MPa

Geopolymer concrete

Fresh density
= 2200 - 2450 kg/m^3
(Normal Weight Aggregates)
= 1800 - 2000 kg/m^3
(Light Weight Aggregates)

Working time available for fresh mixes > 45 minutes

Chemical nature of geopolymer concretes (GPCs)

Molar ratio of SSS		mole/mole	2.2	3.2
AAS/GPS	w/w	kg/kg	0.55	0.55
(A/B)	v/w	litre/kg	0.46	0.47
Oxide ratios in GPCs				
Na_2O/GPS		%	5.9	5.3
SiO_2/GPS		%	3.6	3.2
H_2O/GPS		%	45.5	46.6
Relative values	$[OH^-]$		1.00	0.86
	Na_2O/GPS		1.00	0.89
	SiO_2/GPS		1.00	0.87
	H_2O/GPS		1.00	1.02

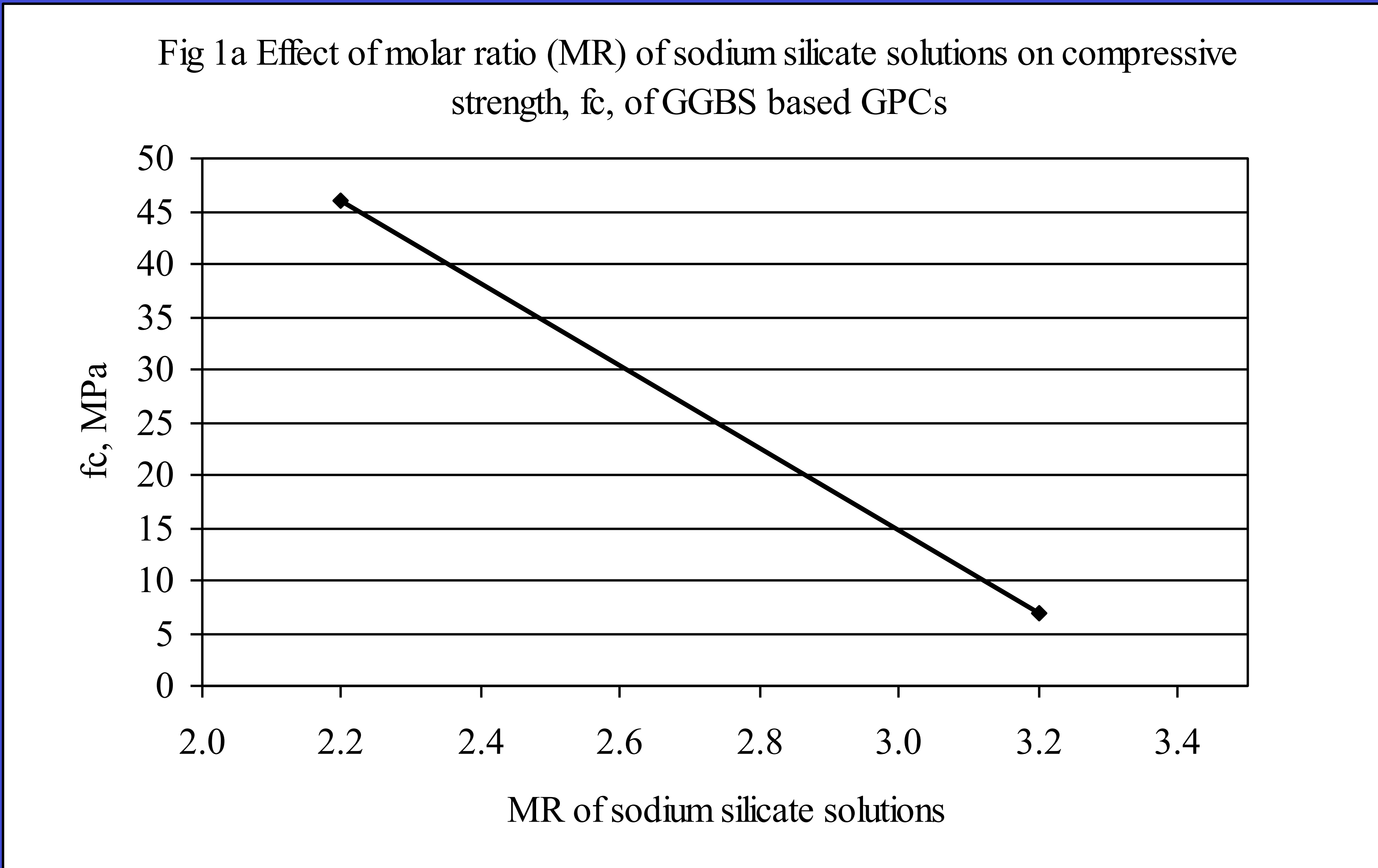


Fig 1a Effect of molar ratio (MR) of sodium silicate solutions on compressive strength, fc, of GGBS based GPCs
fc, MPa
50
45
40
35
30
25
20
15
10
5
0
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
MR of sodium silicate solutions

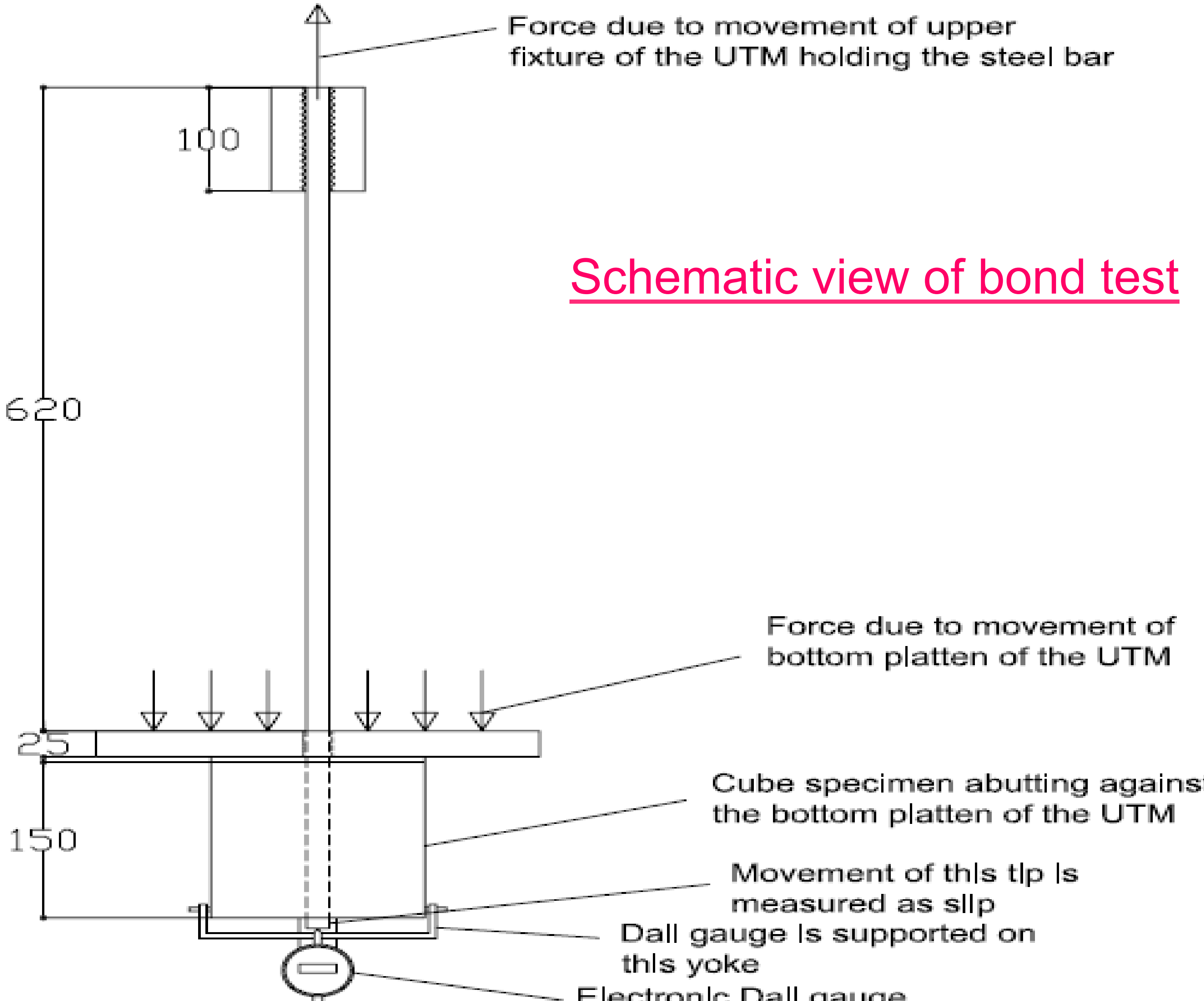
STATISTICS OF STRENGTHS

As per IS:456-2000, Grades of GPCs :
GPC0, GPC25, GPC50, GPC75b, GPC75c
are
60, 50, 50, 40, 40

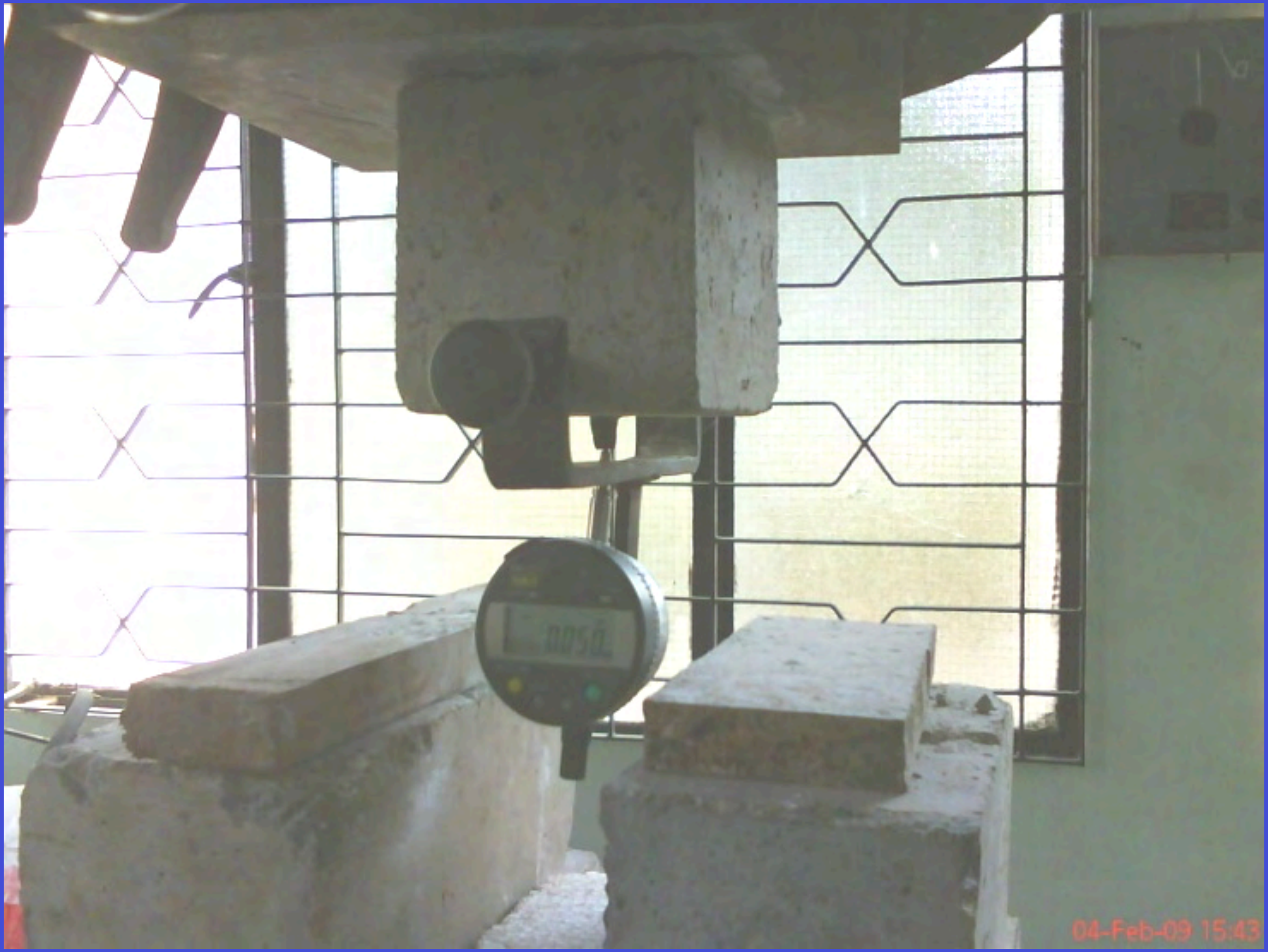
Low values of Kurtosis and Skewness show strength variation in GPCs is representable by Normal Distribution Curve as in case of CCs

Investigation on bond behaviour of GPCC with steel bars

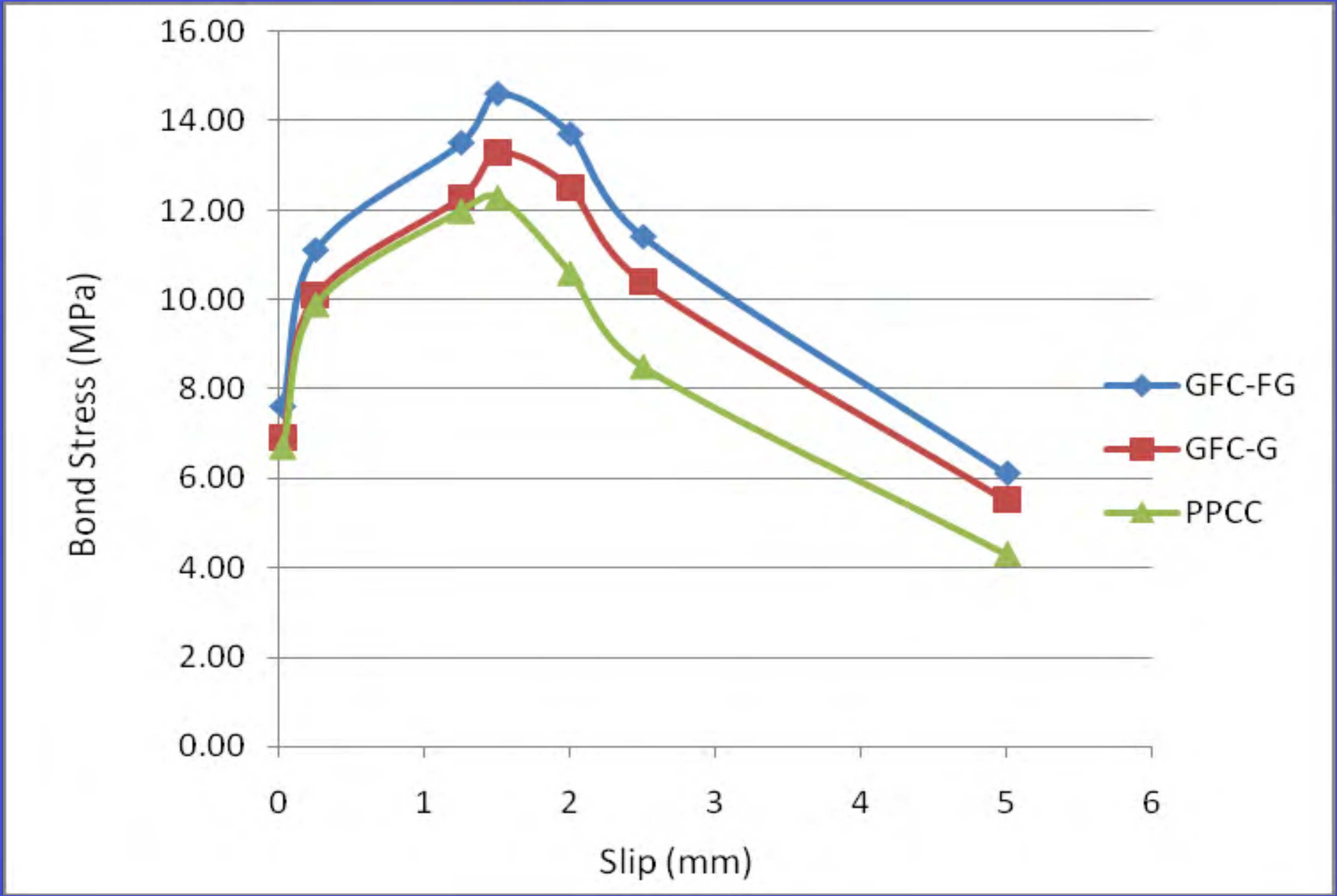
Schematic view of bond test



Bond test set up



Typical bond-slip relationship (12 mm dia)



Evaluation of stress-strain relationship of GPCs

Test Set up for recording stress-strain curve

Stress-strain Models

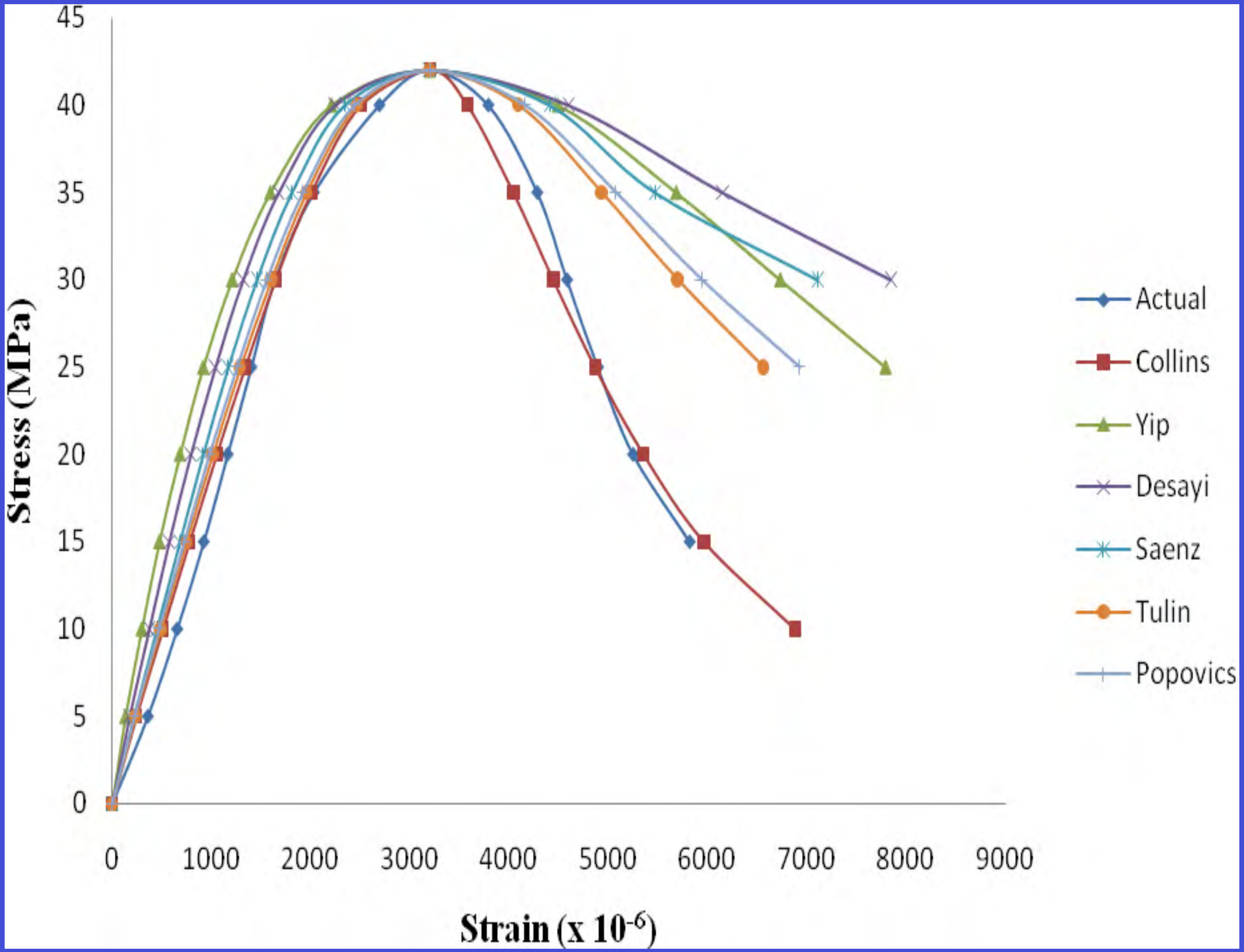
Collins and Mitchell

$$\sigma = \frac{n\,Es\,\varepsilon}{n - 1 + \left(\varepsilon/\varepsilon_o\right)^{nk}}$$

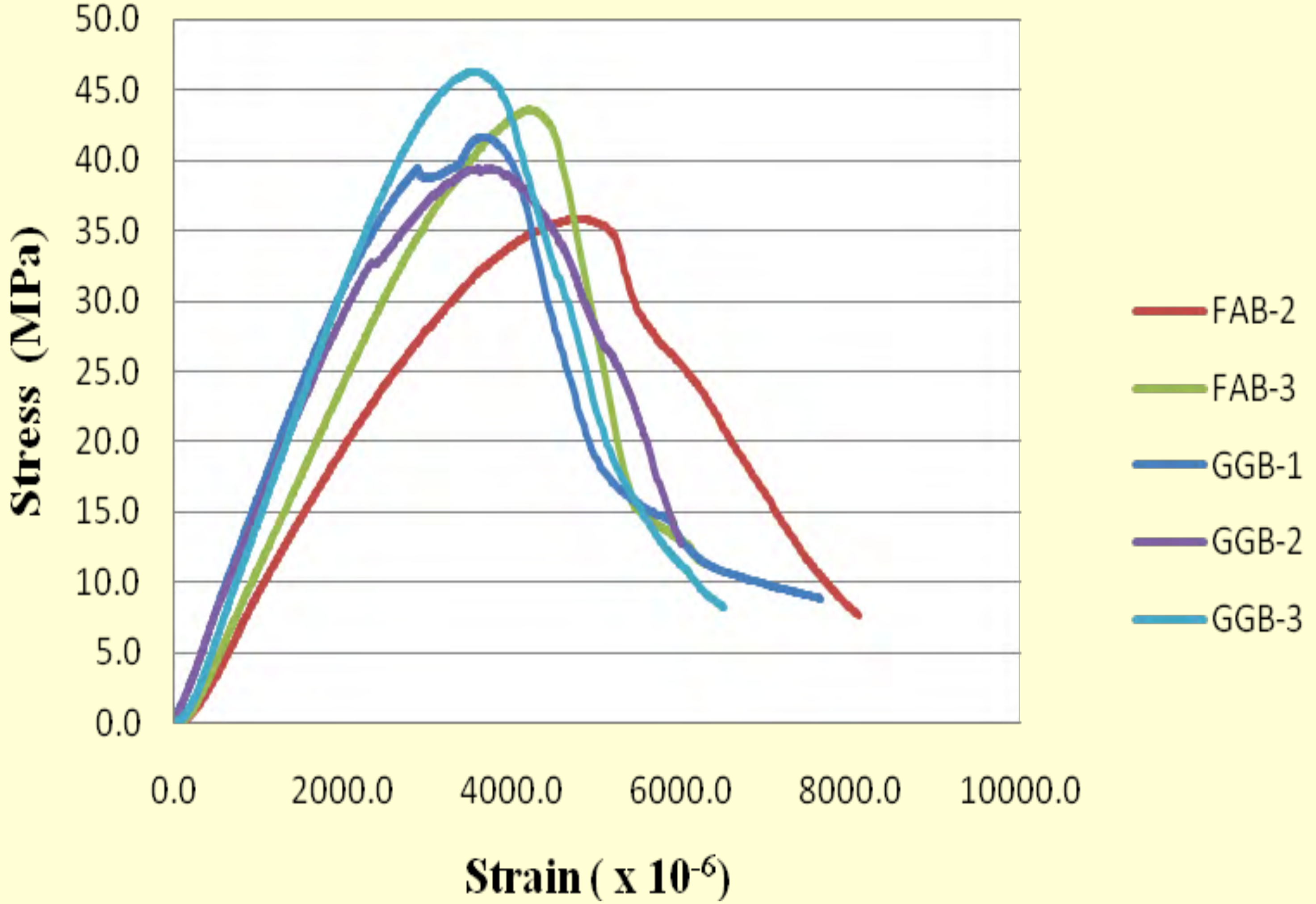
$$k = 0.67 + \frac{\sigma_{c,u}}{62}$$

$$n = 0.8 + \frac{\sigma_{c,u}}{17}$$

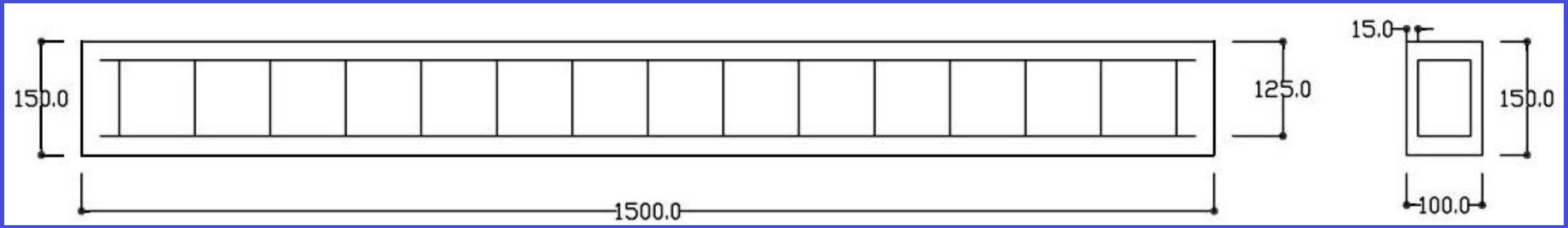
Typical Stress-Strain curves for GPCC



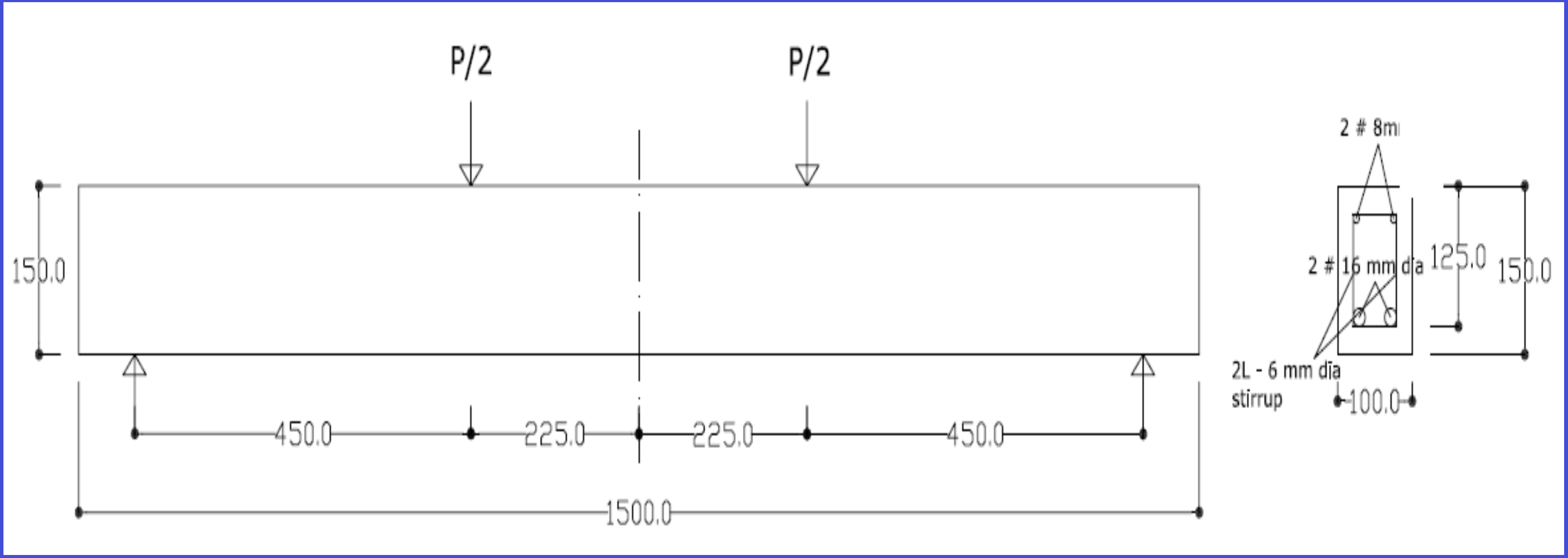
Stress-strain Characteristics



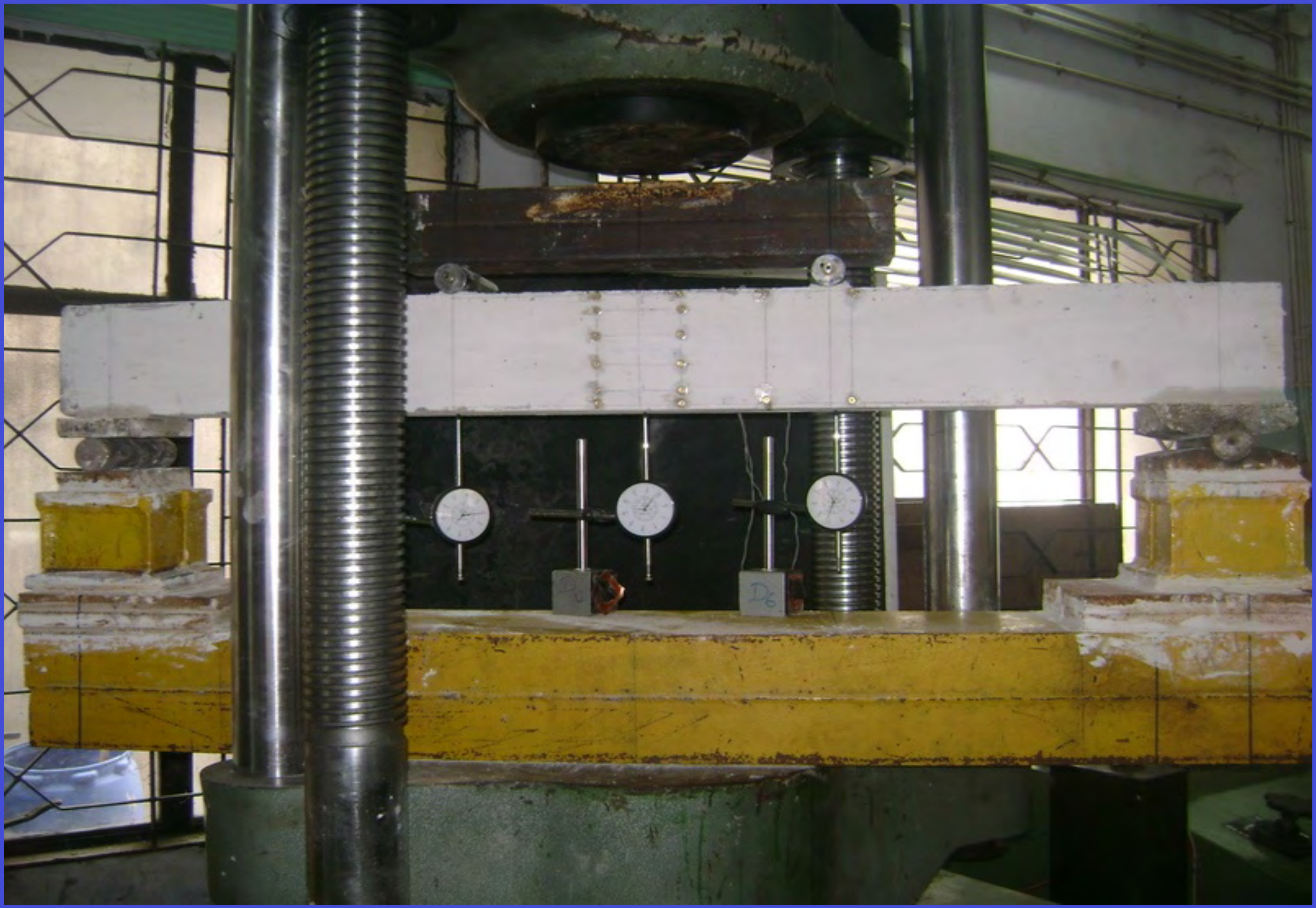
Evaluation of reinforced GPC beam specimens in flexure



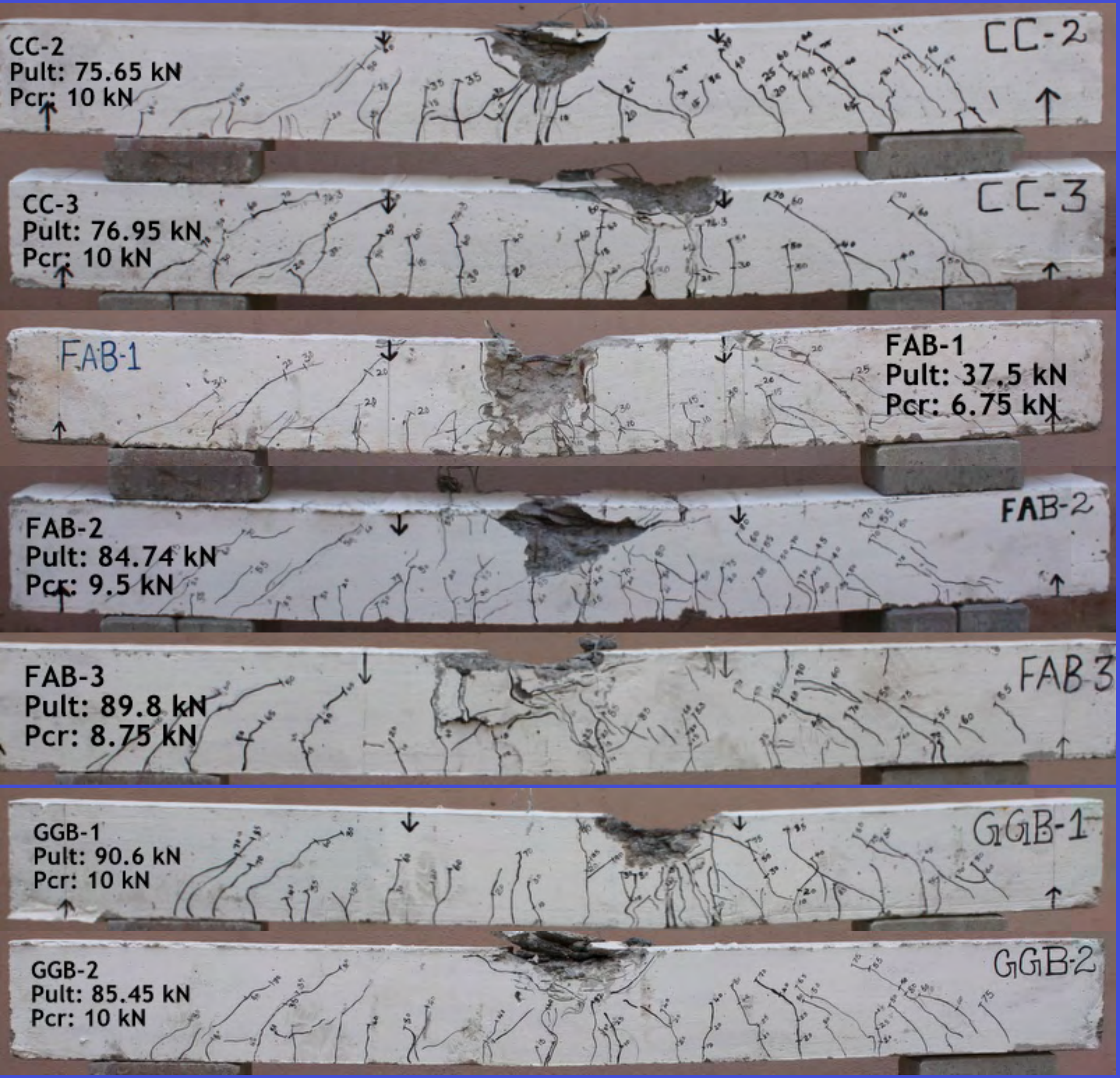
Geometry of Beam Specimen



Line sketch of test setup



Experimental setup for flexural test



Crack patterns & failure modes in beam specimens

GPC behaviour in flexure

- Performance of GPCs is similar to that of conventional concretes, with regards to :
  - compressive strength, modulus of elasticity and strain at peak loads

- Load-deflection characteristics, cracking pattern & failure modes of reinforced GPCC beams were similar to reinforced PPCC beams

- Reinforced GPC beams have marginally higher flexural capacity than reinforced PPCC beams for the same order of compressive strength

Evaluation of alkalinity of pore solutions of concretes

Flame Photometry Test Results on Geopolymeric & Portland Cement Based Systems

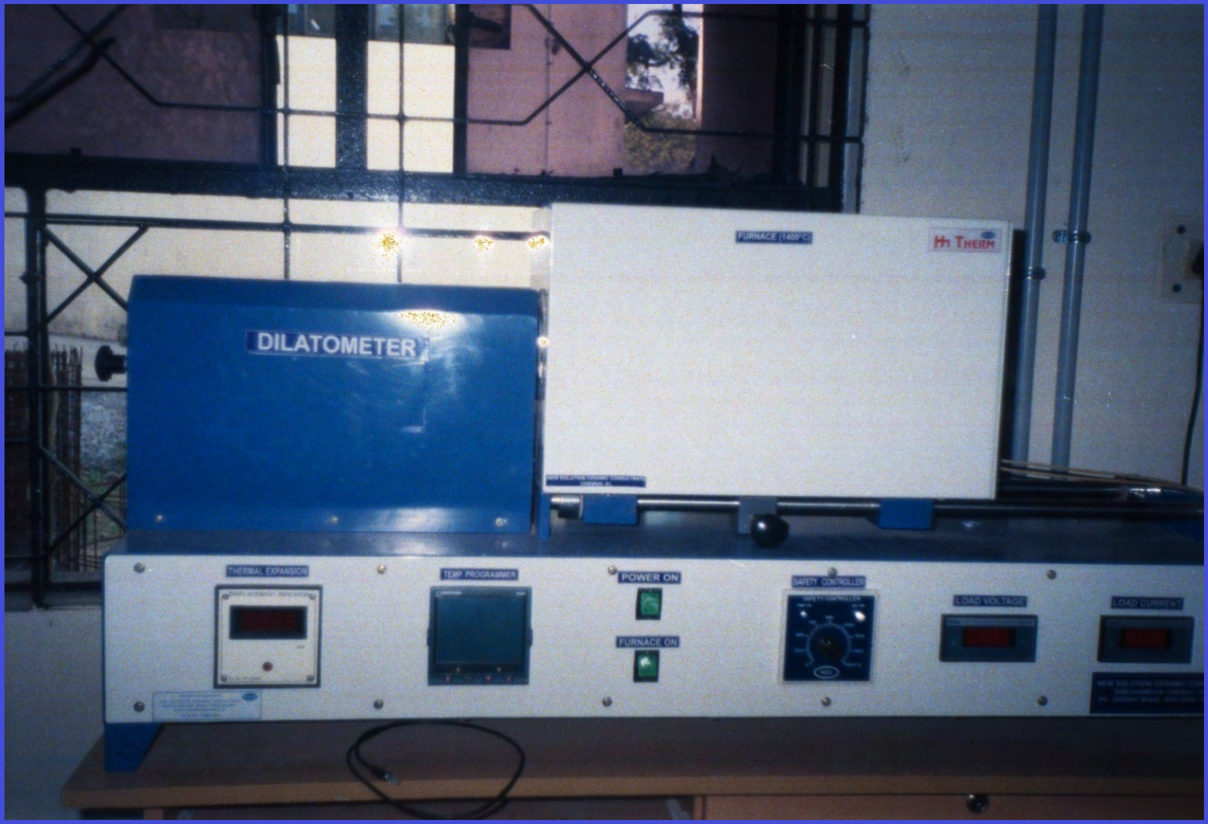
Sl No	Binder type	Dilution for FP test	FP Reading		Soln of binder paste	
			Na^+ ppm	K^+ ppm	$[OH^-]$ mMol	=14+ log10(OH)
1	Cement (OPC cement)	1	47	17	830	13.9
2	Cement + Fly Ash	1	45	23	854	13.9
3	Cement + Fly Ash	1	37	22	729	13.9
4	Cement+Silica fume	1	44	19	804	13.9
5	FAB-3	1	29	2	876	13.9
6	GGB-1	1	119	23	385	13.6
7	FAB-2	1	29	0.3	846	13.9
8	FAB-1	1	31	0.1	900	14.0
9	GGB-2	1	34	2	1021	14.0
10	GGB-3	1	24	0.5	704	13.8

ALKALINITY OF PORE SOLUTIONS

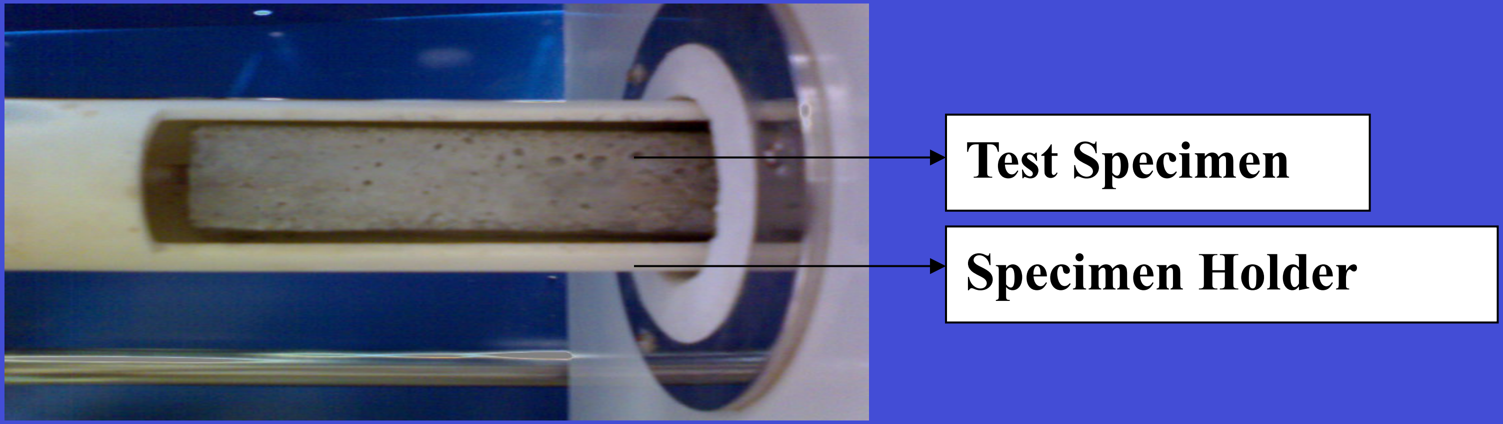
Alkalinity of pore solutions of all the concretes studied are similar

(GPCs, Portland cement concretes with fly ash, silica fume)

Tests for Coefficient of Thermal Expansion of Geopolymeric Mortars



Dilatometer for thermal expansion measurement



Specimen inside dilatometer

Specimen size: 100*25*25 mm (prism)

SPECIMEN BEFORE TESTING

SPECIMEN AFTER TESTING

COMPARISION of

COEFFICIENTS of LINEAR THERMAL EXPANSION (CLTE)

From literature:

- Cement paste 9.0 to 25.0 $*10^{-6}/^{o}C$
- Cement concrete 6.1 to 12.1 $*10^{-6}/^{o}C$
- Rocks 1.8 to 12.0 $*10^{-6}/^{o}C$

From present study

- Cement mortar 9.2 to 16.8 $*10^{-6}/^{o}C$
- Geopolymer mortar 4.3 to 12.0 $*10^{-6}/^{o}C$

Steel fibre reinforced concretes

Fibre reinforced geopolymer concretes with sintered fly ash lightweight aggregates

Mix ID	Proportions by weight				A/B	Fibre Vol. Per m^3	Fresh density
	GGBS	FA	Sand	LWA		%	kg/m^3
$GSFF_{0.25,0}$	0.75	0.25	1.5	1.5	0.55	0	1970
$GSFF_{0.25,0.5}$	0.75	0.25	1.5	1.5	0.55	0.5	1982
$GSFF_{0.25,1}$	0.75	0.25	1.5	1.5	0.55	1	2000

Fibre reinforced geopolymer concretes with normal weight aggregates

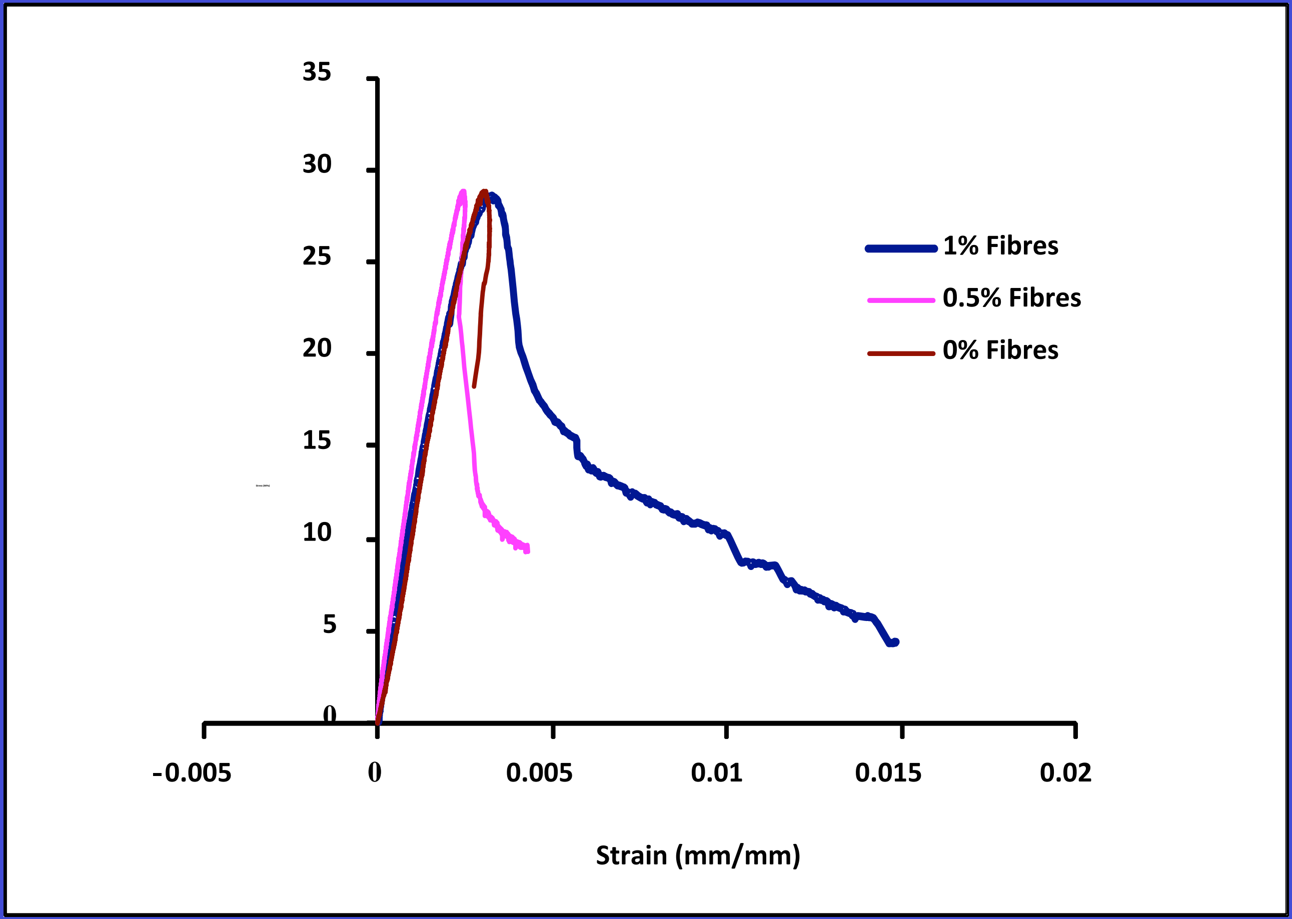
Mix ID	Proportions by weight				A/B	Fibre Volume Per m^3	Fresh density
	GGBS	FA	Sand	LWA		%	kg/m^3
GPC 25,0	0.75	0.25	1.5	1.5	0.55	0	2370
GPC 25,0.5	0.75	0.25	1.5	1.5	0.55	0.5	2392
GPC 25,1	0.75	0.25	1.5	1.5	0.55	1	2410

SFR-LWC

Mix ID	f_c MPa	f_t MPa	f_b MPa	E GPa	f_t/f_c %	f_b/f_c %	% Change due to fibre		
							f_c	f_t	f_b
GSFF 0.25,0	34	2	4	12-15	7	12			
G S F F 0.25,0.5	40	4	5	12-15	10	12	19	65	12
G S F F 0.25,1	39	5	6	11-12	13	12	17	118	13

SFR-NWC

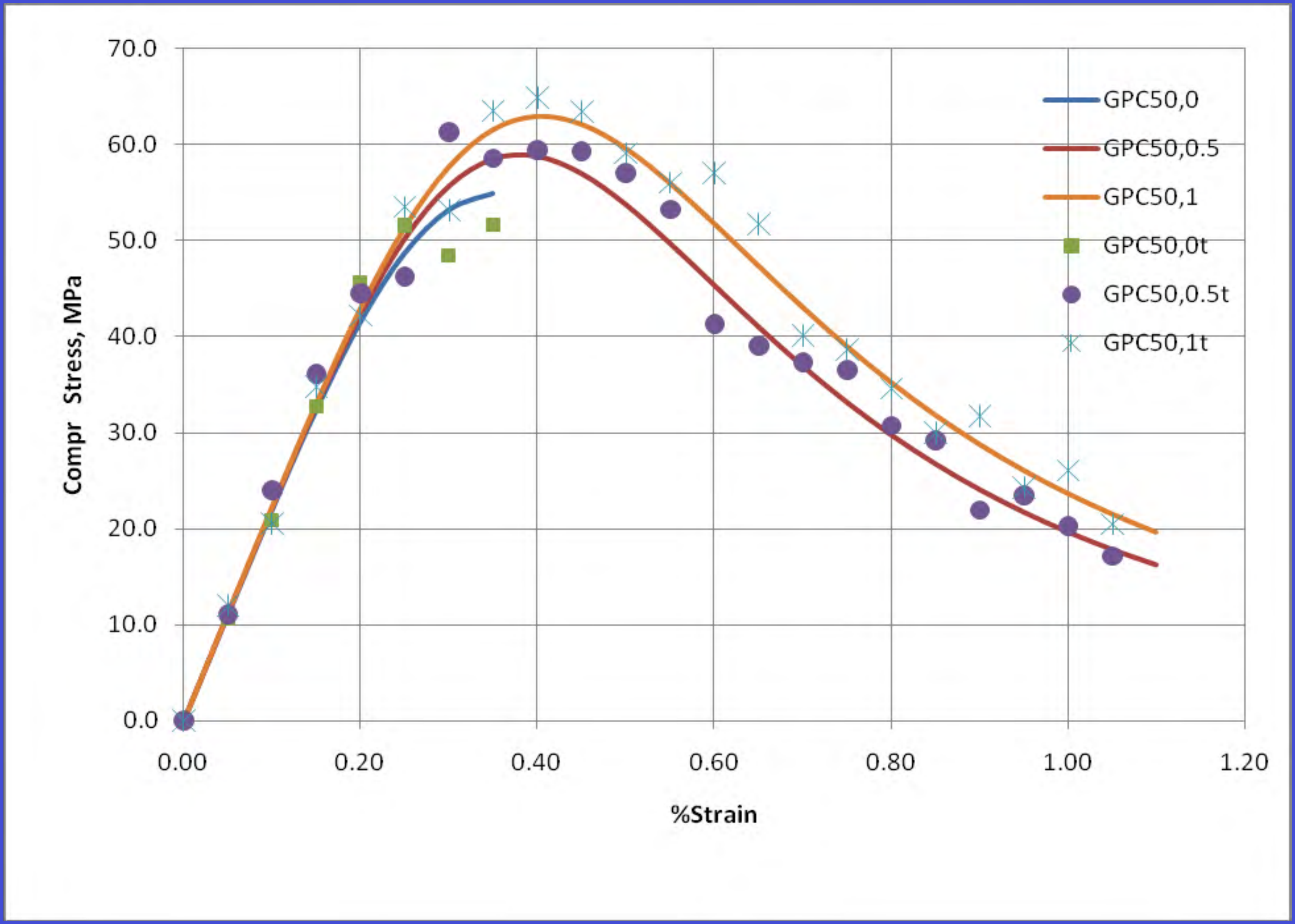
Mix ID	V_f %	σ_{cu} MPa	0.4 * σ_{cu} MPa	Long. strain (ε) (mm/mm) at			β	ME GPa
				σ_{cu}	$f_{0.4\sigma cu}$	failure		
$GPC_{25,0}$	0	60	24	0.003592	0.1026	0.0047	3.22	24
$GPC_{25,0.5}$	0.5	63	25.2	0.0039	0.1085	0.0084	3.20	23
$GPC_{25,1}$	1	67	26.8	0.0041	0.1153	0.0168	3.21	25



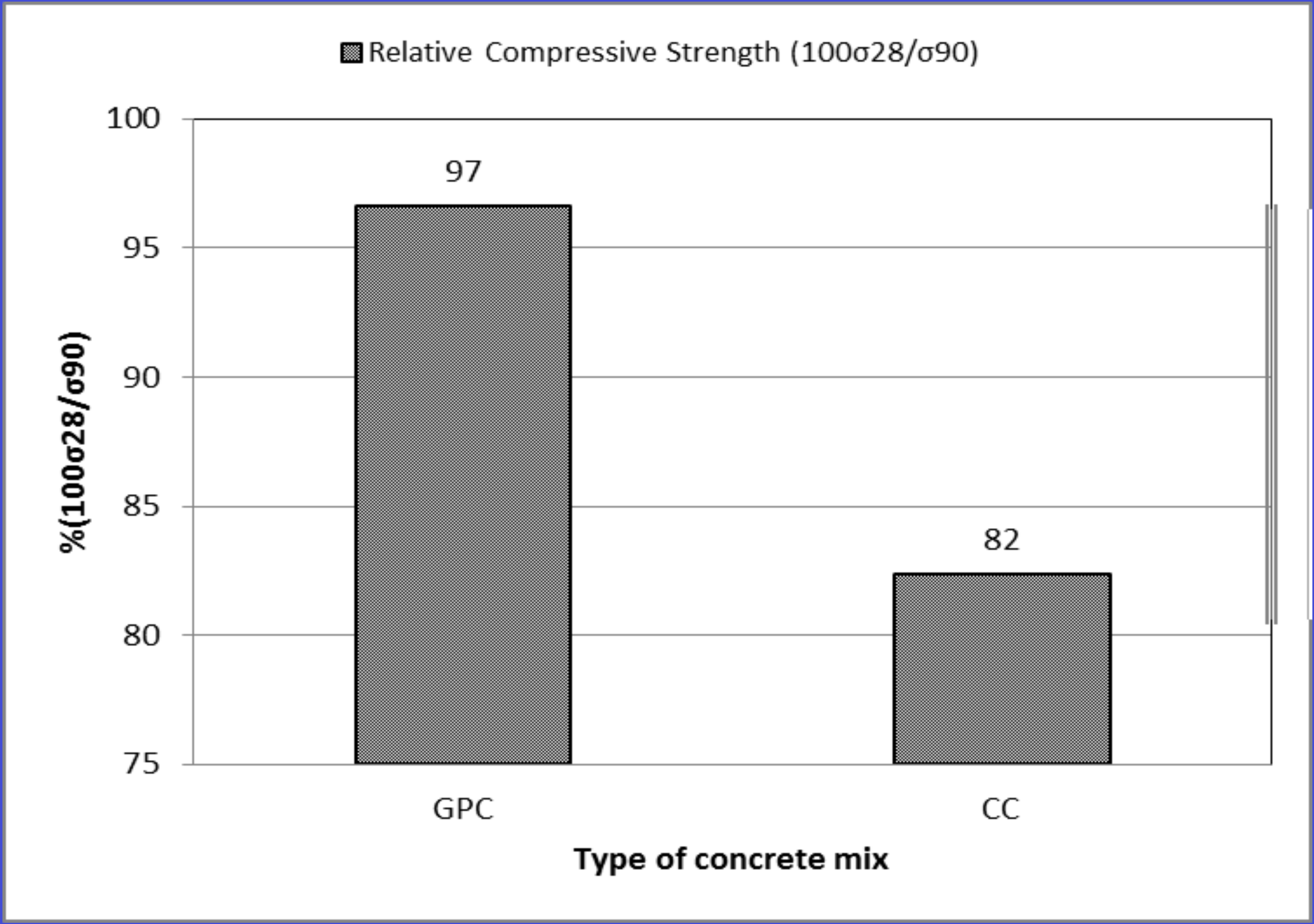
Stress Strain curve for Steel Fibre Reinforced Lightweight GPCs

Stress-strain relationship for Fibre Reinforced concretes

Stress-strain curve for Normal Weight GPC mix GPC50



Rate of Strength Development



%Compressive Strengths at 28 day Relative to 90 day $(100*\sigma_{28}/\sigma_{90})$

Ecological characteristics of concretes

Data for Ecological Computations

	Embodied Energy MJ/kg	Embodied Carbon di oxide $kgCO_2e/kg$	Cost Rs/kg
Fly ash	0.1	0.008	1
GGBS	1.6	0.083	3
OPC	5.5	0.93	5
Sand	0.15	0.005	1
Fly Ash Aggregate	0.43	0.064	1
Coarse Aggregate	0.083	0.005	1

Data for Ecological Computations

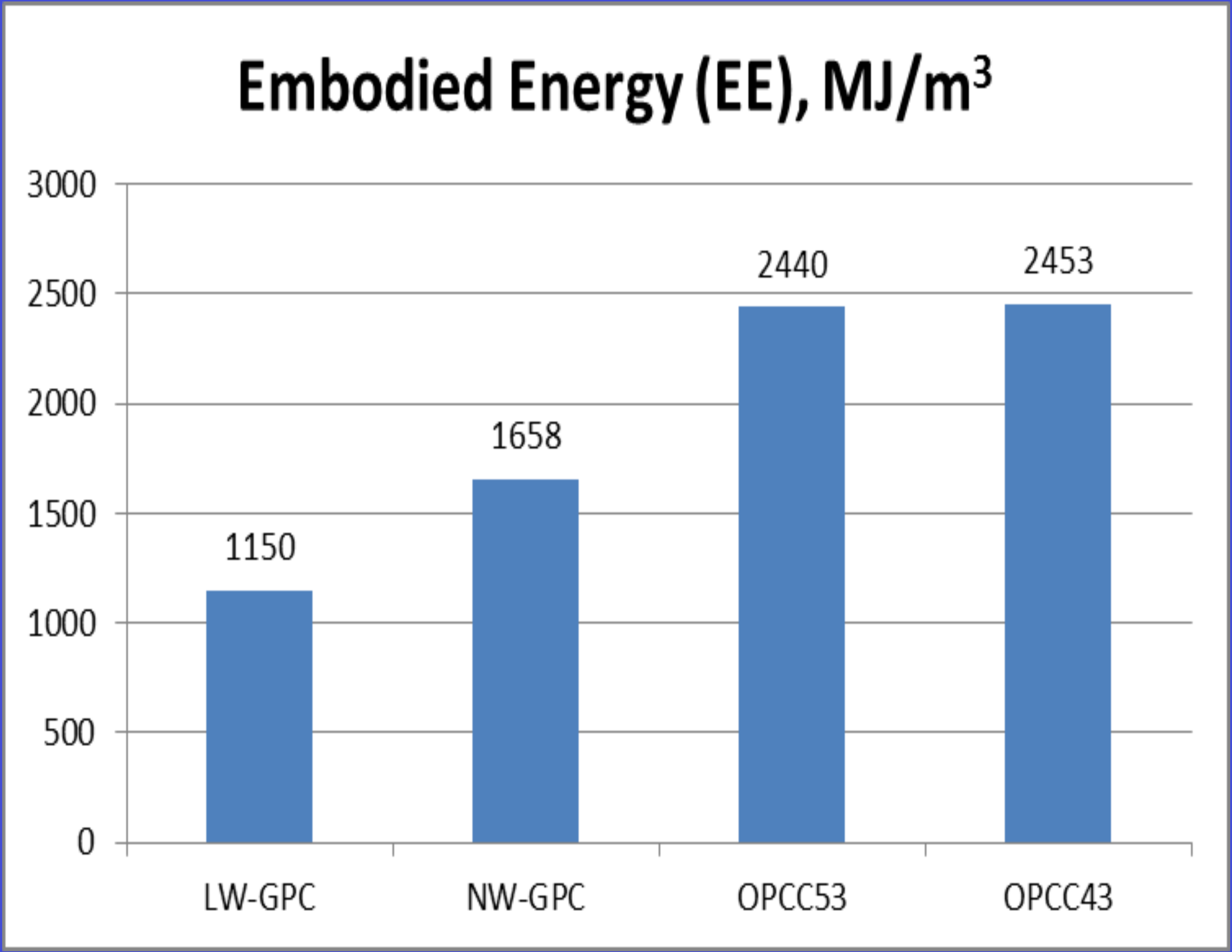
	Embodied Energy MJ/kg	Embodied Carbon di oxide $kgCO_2e/kg$	Cost Rs/kg
Sodium Hydroxide flakes	3	0.015	20
Sodium Silicate Solution	3	0.015	12
Distilled Water	0	8E-04	2
Water	0	8E-04	0
Suprplasticiser	9	0.38	50

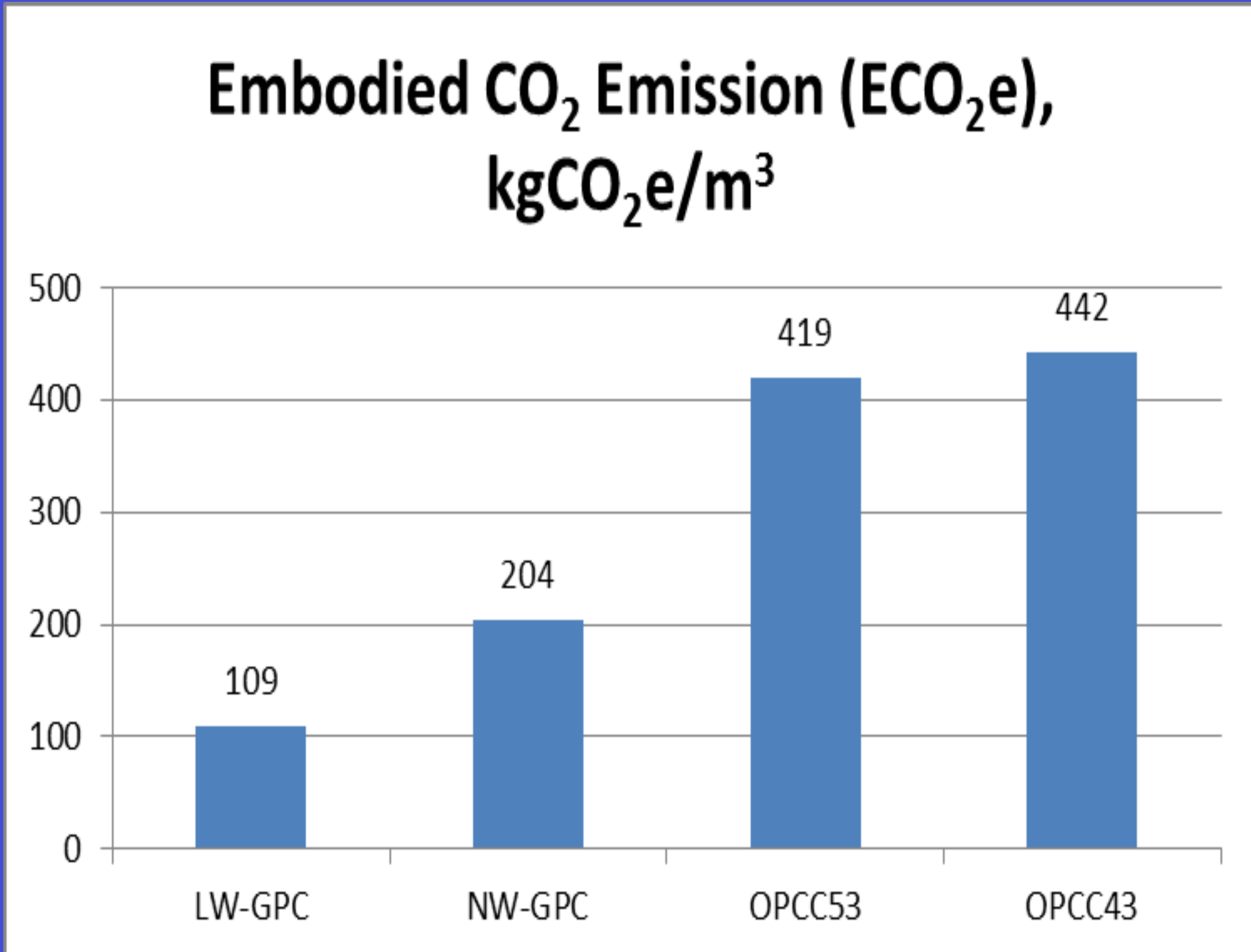
Ecological Comparison of Light Weight-Geopolymer Concrete with OPC Concrete

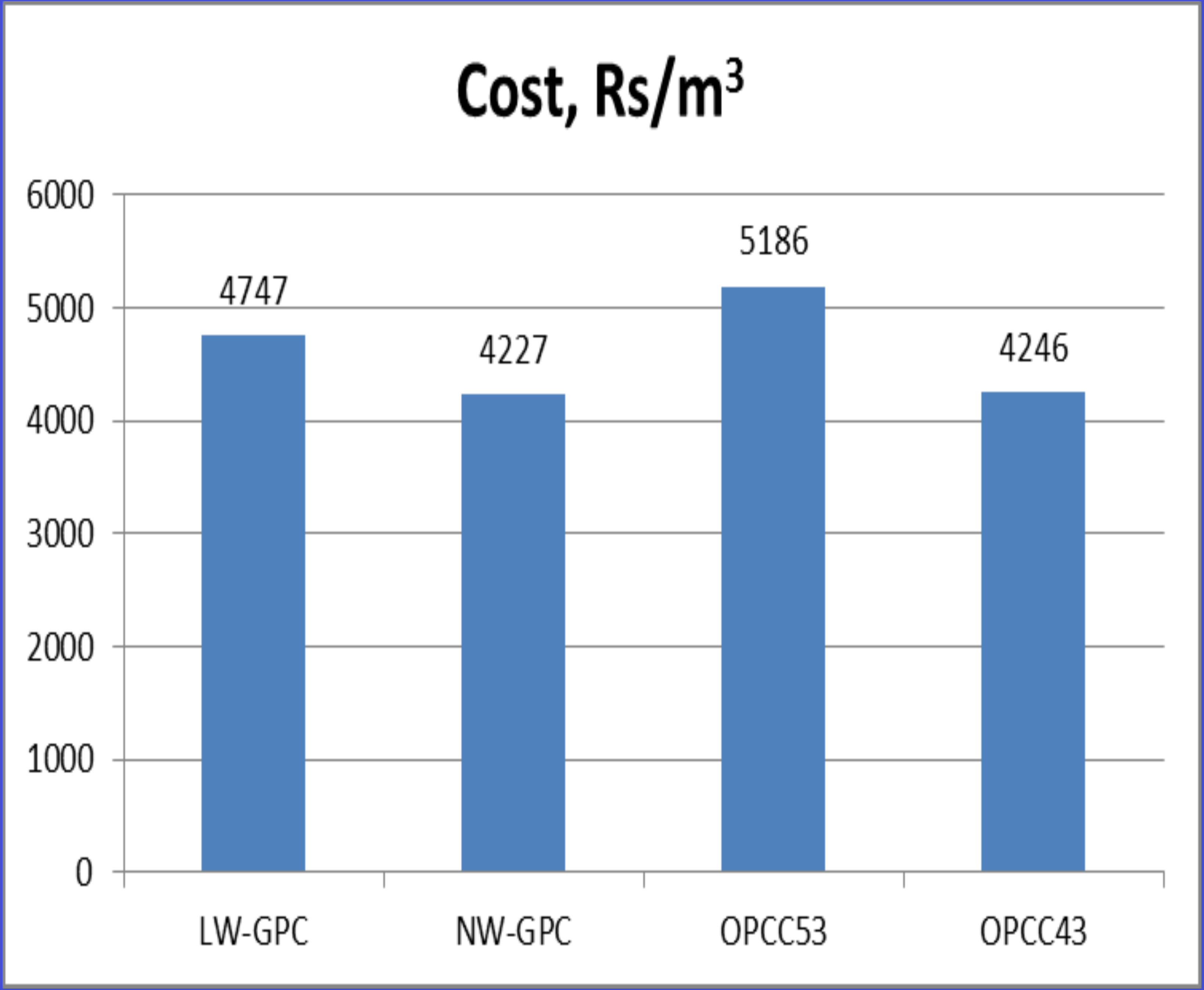
Mix ID		LW-GPC	OPCC	% Relative to OPCC	Prefer
Embodied Energy, EE	MJ/m^3	1150	2440	47.1	Lower
Embodied CO_2 Emission, ECO_2e	$kgCO_2e/m^3$	109	419	26.0	
Material cost	Rs/m^3	4747	5186	91.5	
fc28,	MPa	34	59	57.6	
Density, D	kg/m^3	1970	2380	82.8	
EE/D	MJ/kg	0.58	1.03	56.3	
ECO_2e/D	$kgCO_2e/kg$	0.06	0.18	33.3	
Cost/D	Rs/kg	2.41	2.18	110.6	Higher
EE/fc28	MJ/kg	33.8	41.4	81.6	Lower
$ECO_2e/fc28$	$kgCO_2e/kg$	3.2	7.1	45.1	
Cost/fc28	Rs/kg	139.6	87.9	158.8	Higher

Ecological Comparison of NW-GPC with OPCC

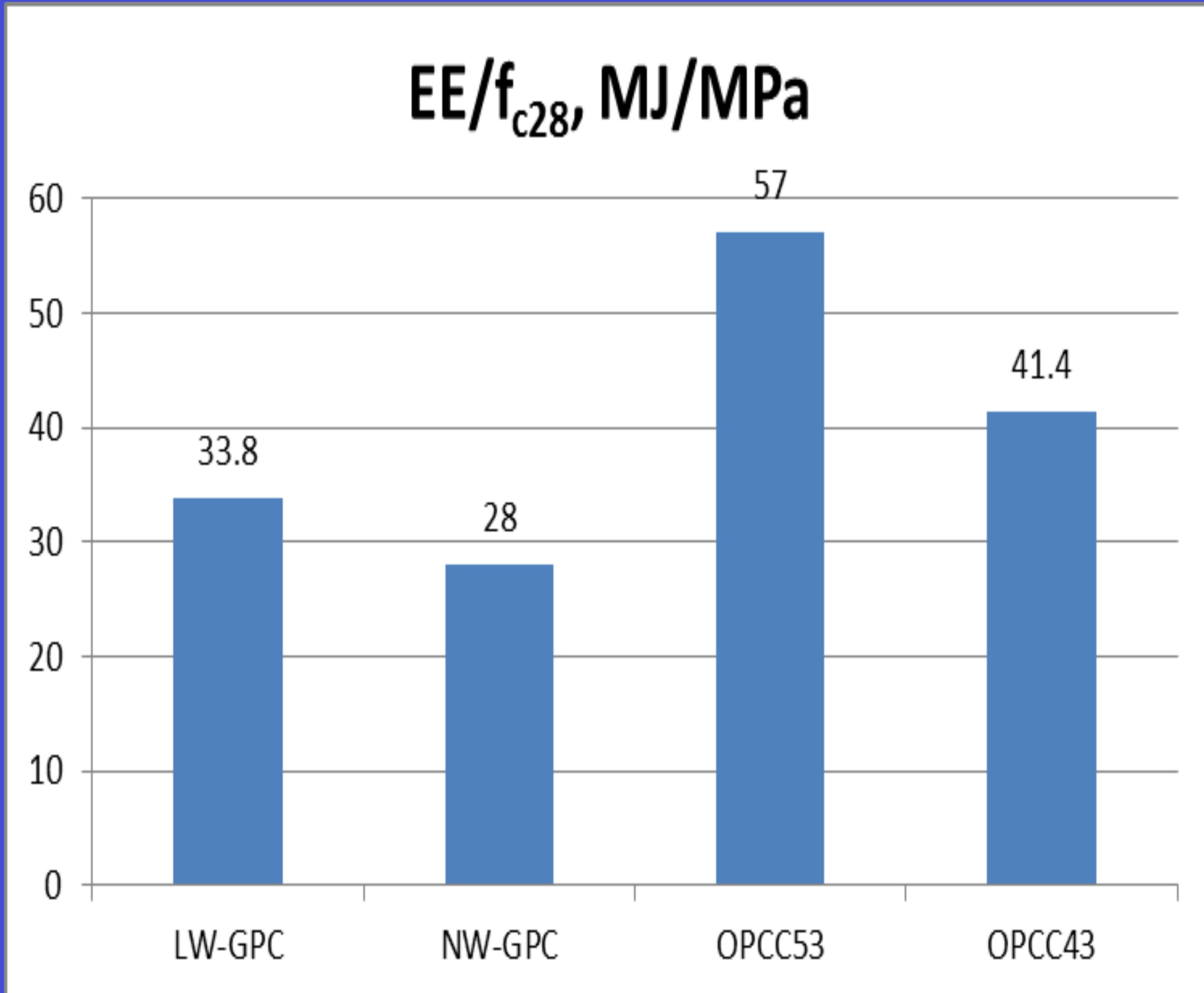
Parameter Detail		Unit	GPC25	OPCC
1	D	kg/m^3	2360	2365
2	EE	MJ/m^3	1658	2453
3	ECO_2e	$kgCO2e/m^3$	204	442
4	Cost	Rs/m^3	4227	4246
5	fc28	MPa	60	43
6	D/f_{c28}	kg/MPa	39	55
7	EE/f_{c28}	MJ/MPa	28	57
8	ECO_2e/f_{c28}	$kgCO_2e/MPa$	3	10
9	$Cost/f_{c28}$	Rs/MPa	70	99
10	Durability	Score (%)	76	11

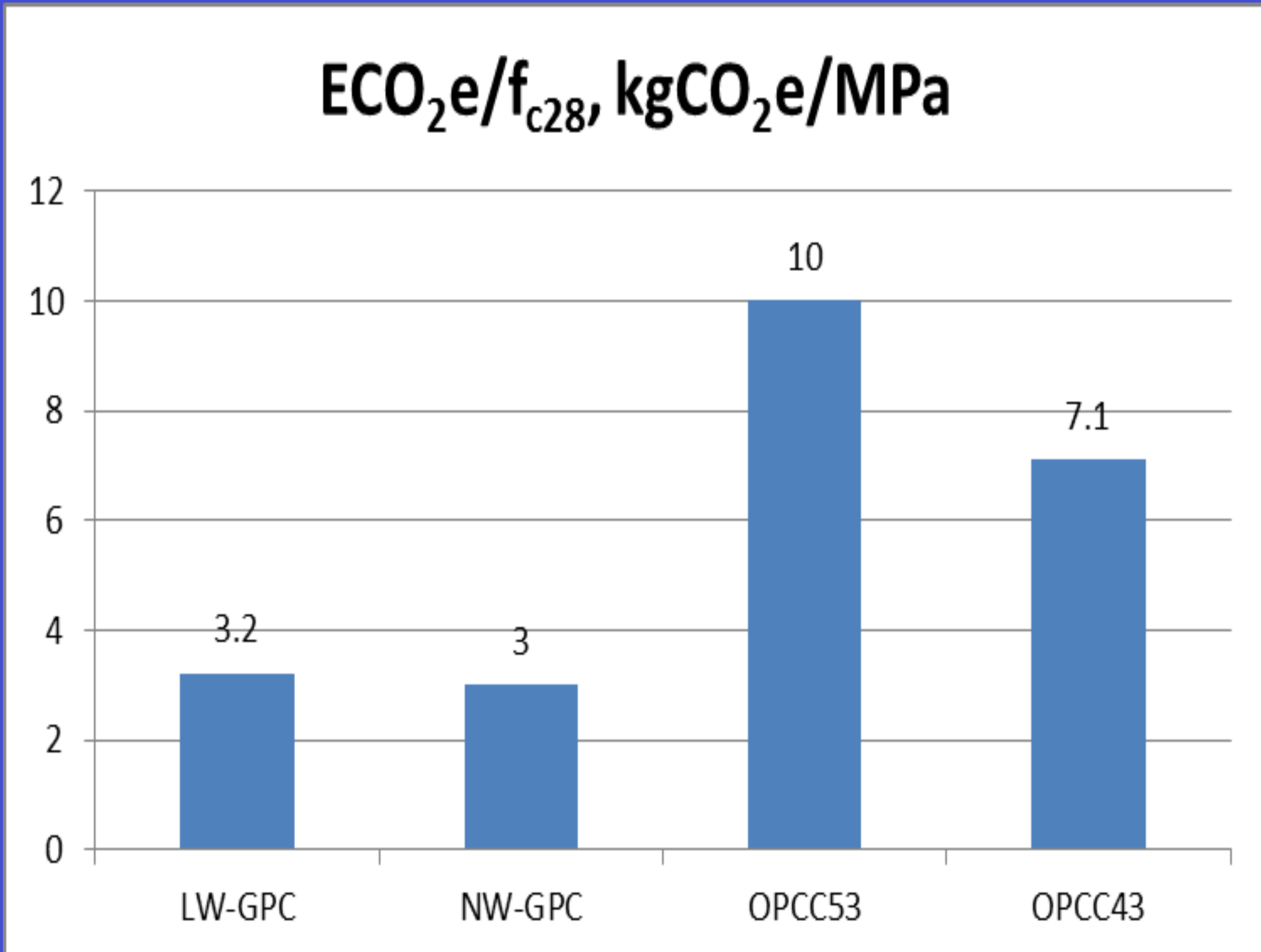

Embodied Energy (EE), MJ/m3
3000
2500
2000
1500
1000
500
0
1150
1658
2440
2453
LW-GPC
NW-GPC
OPCC53
OPCC43


Embodied CO2 Emission (ECO2e), kgCO2e/m3
500
400
300
200
100
0
109
204
419
442
LW-GPC
NW-GPC
OPCC53
OPCC43



Cost, Rs/m³
6000
5000
4000
3000
2000
1000
0
4747
4227
5186
4246
LW-GPC
NW-GPC
OPCC53
OPCC43


EE/f$_{c28}$, MJ/MPa
60
50
40
30
20
10
0
33.8
28
57
41.4
LW-GPC
NW-GPC
OPCC53
OPCC43



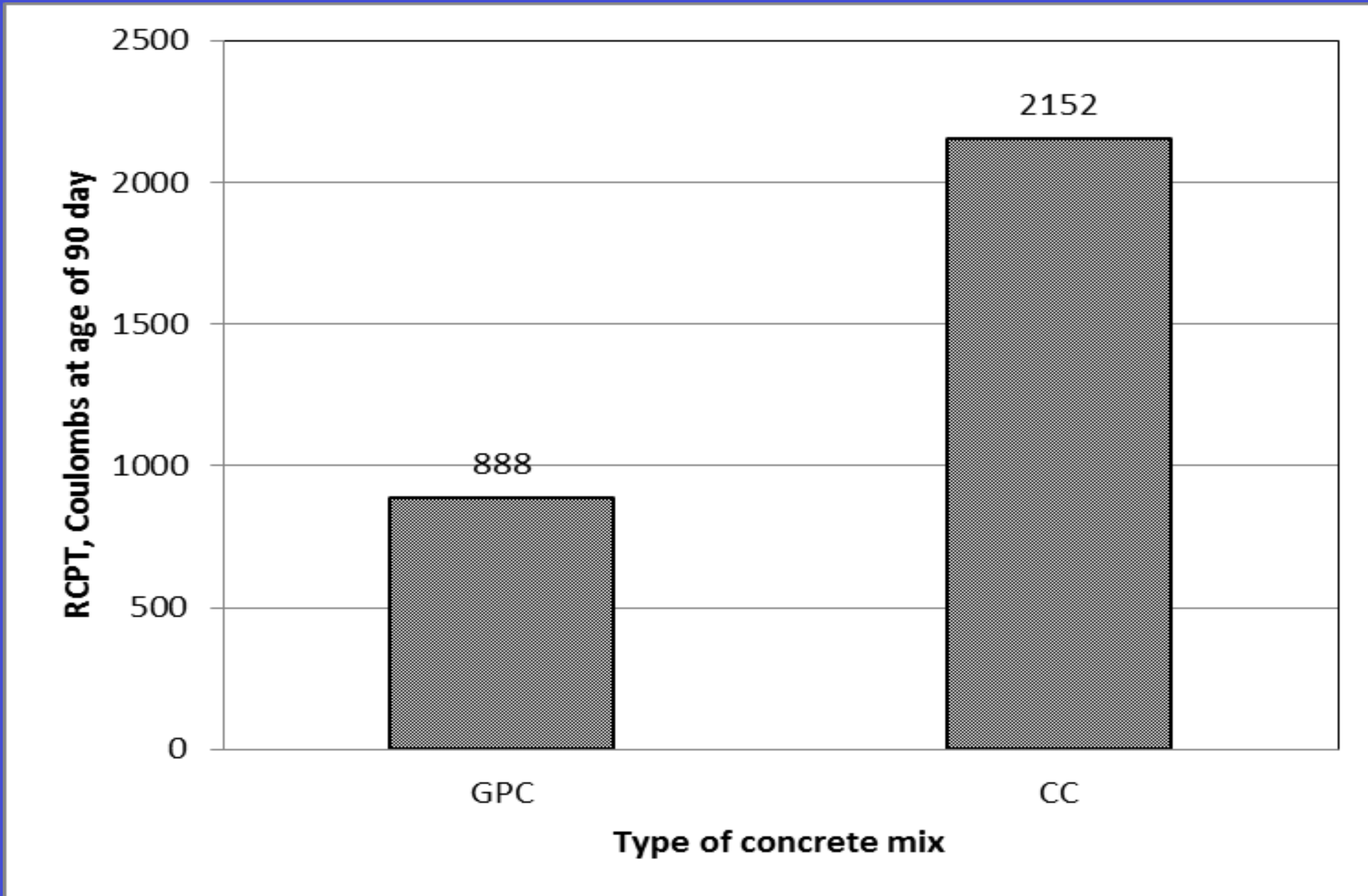
ECO_2e/f_{c28}, $kgCO_2e/MPa$
12
10
8
6
4
2
0
3.2
3
10
7.1
LW-GPC
NW-GPC
OPCC53
OPCC43

Durability characteristics of concretes

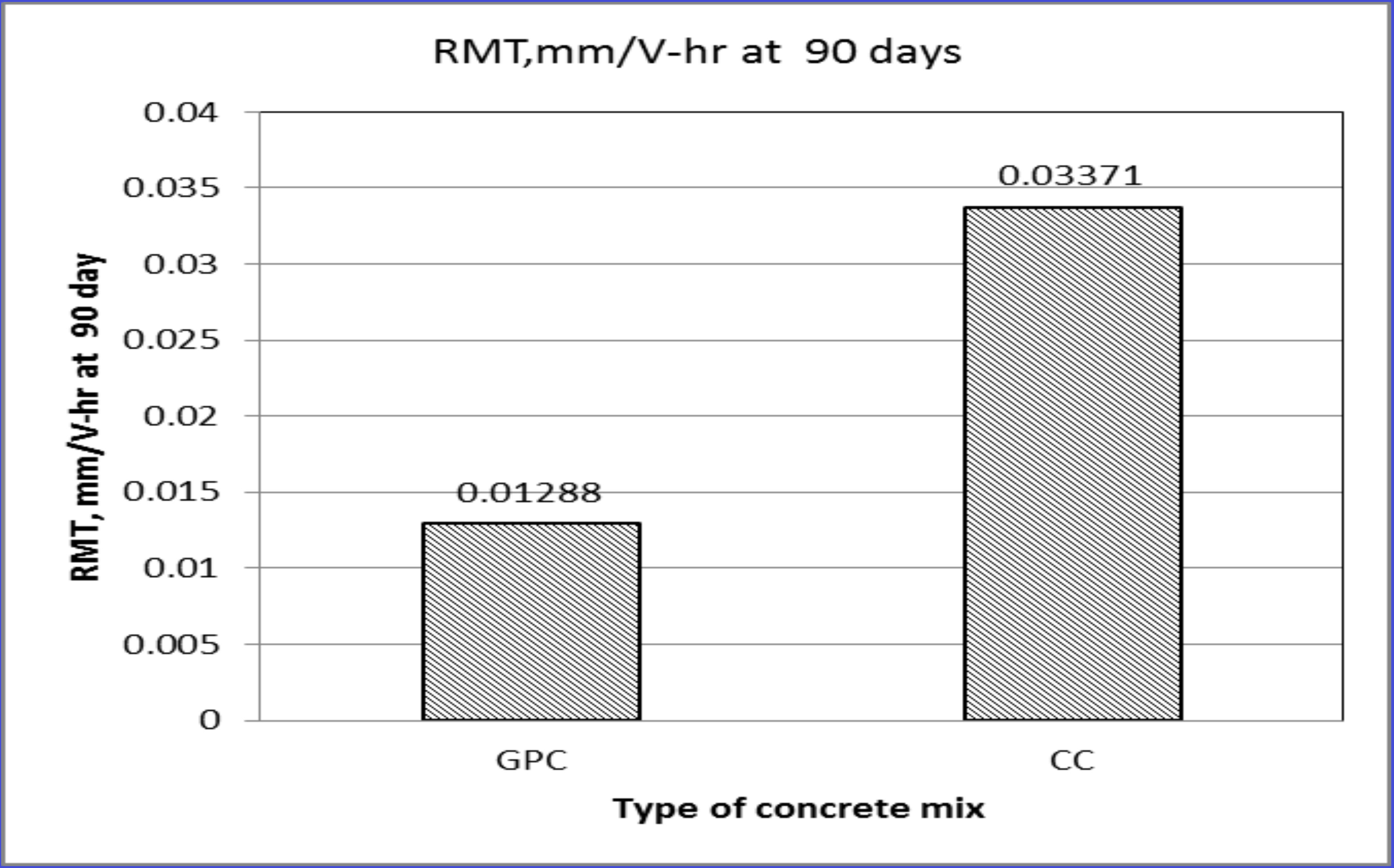
10% Sulphuric acid attack (60 days)

PPCC

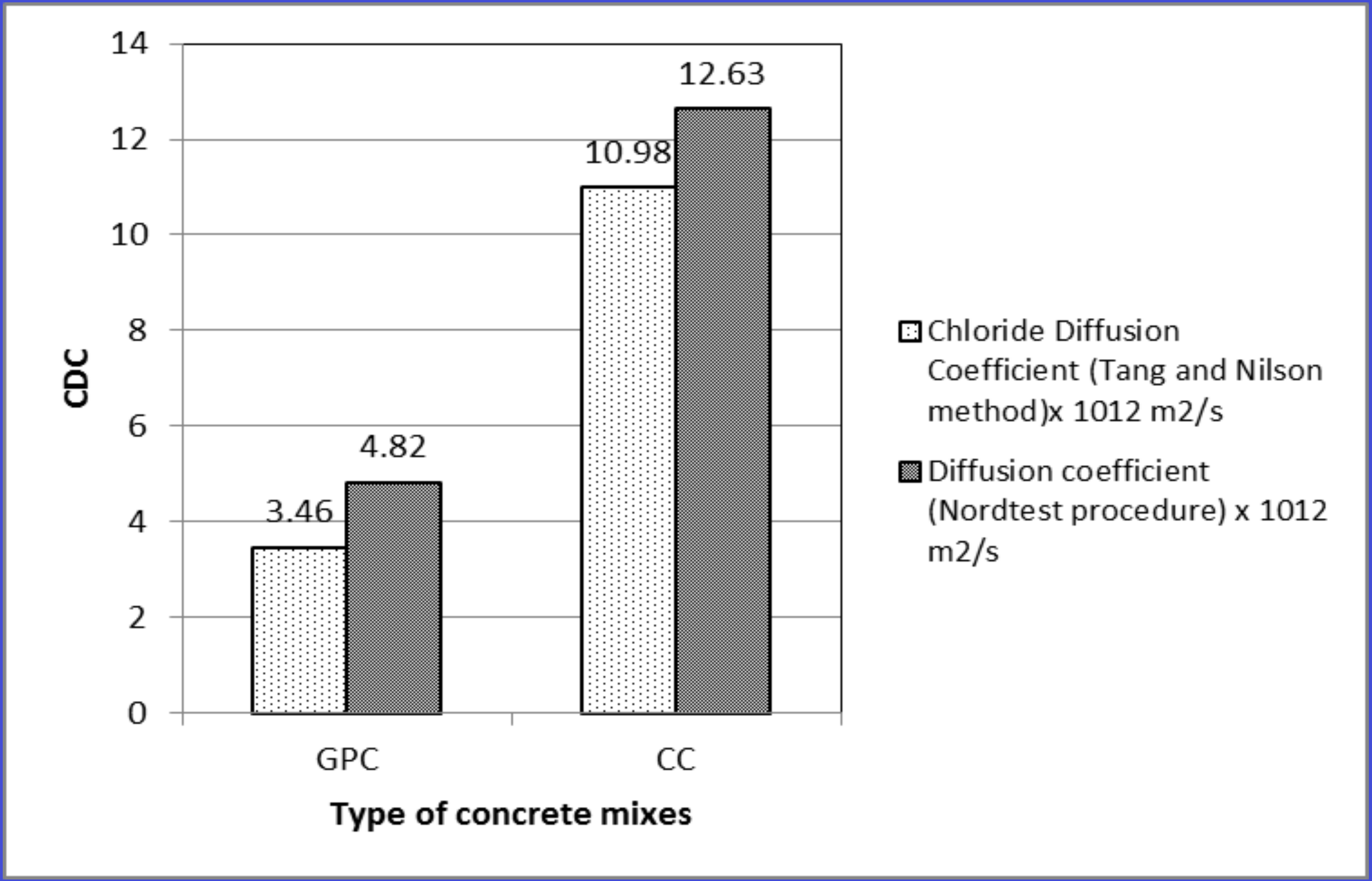
GPCC



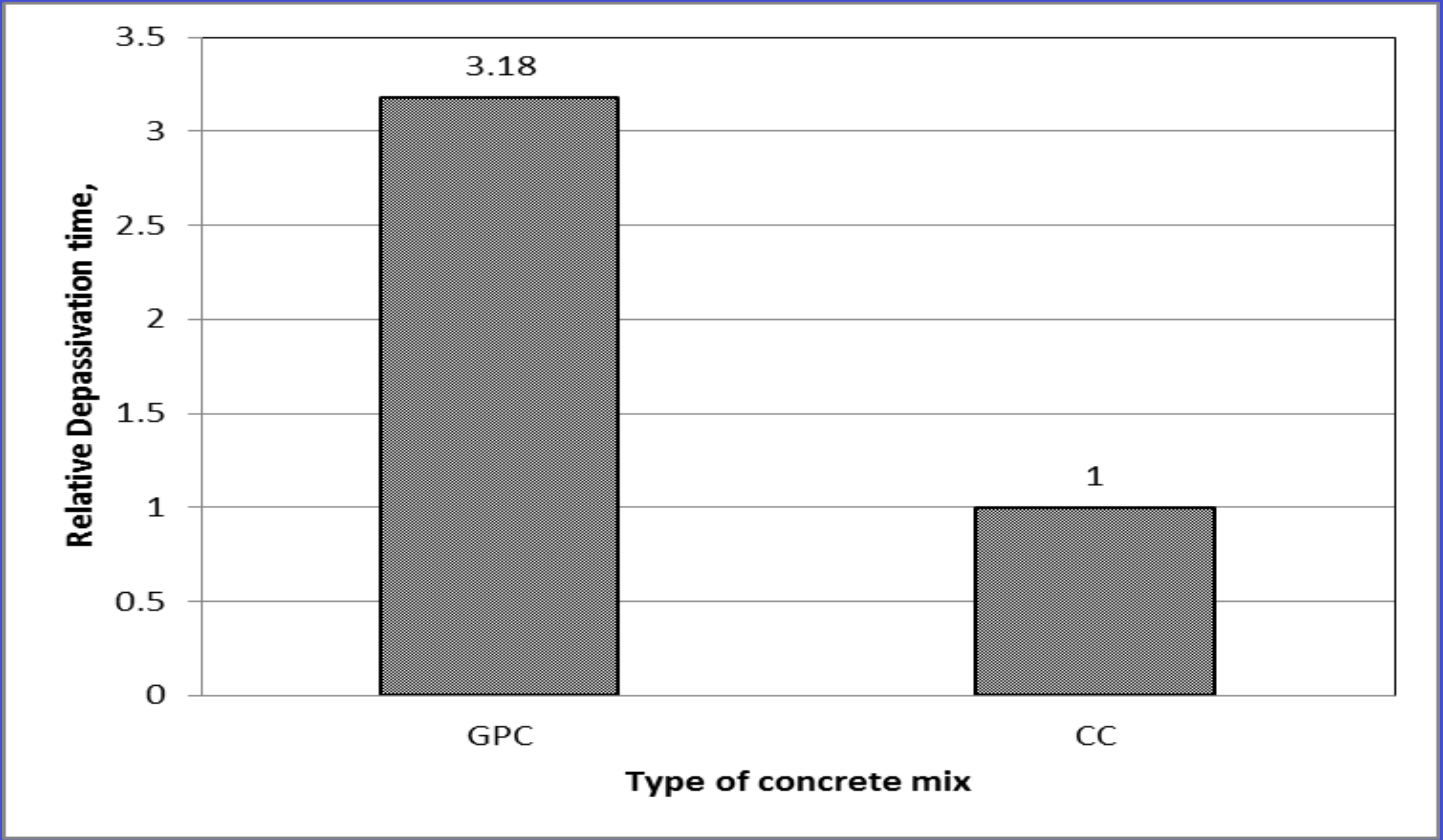
Rapid Chloride Permeability Test (Coulombs)



Rapid (Chloride) Migration Test



Chloride Diffusion Coefficient (*$^{-12}$ cm^2/sec)



Relative depassivation time (for initiation of corrosion of steel) for build-up of threshold Cl- concentration

Practical applications of geopolymer blocks

Trial factory production of GPC blocks

Topping of Road with GPC (Geopolymer Concrete Pavement)




Patch (Spot) Repair of Concrete Roads

Geopolymer Concrete for fast Jointing of Precast Elements

Geopolymer Concrete as fast setting material in joints of Precast Elements

Testing of Slab with GPC Joint after 24 hours

GPC Paver Blocks

S No	%FA in GSM	%Sand in Fine Aggr	Mix proportions (by weight)				Compressive strength	
			GSM	Fine Aggr	Coarse Aggr	A/B	MPa	% Increase due to Sand addition
1	0	0	1	4.82	0.61	0.70	25.2	
2	0	24	1	4.73	0.62	0.70	33.2	32
3	25	0	1	4.82	0.61	0.70	25.6	
4	25	24	1	4.73	0.62	0.70	38.1	49
5	50	0	1	4.82	0.61	0.70	15.1	
6	50	24	1	4.73	0.62	0.70	15.1	0

FIELD TRIALS

GP Concrete Road

Geopolymer Paver Blocks

Size 20 x 9.5 x 9 cm

Weight = 3.5 kg

CONCLUDING REMARKS

A combination of Fly ash and GGBS produces geopolymer by action of sodium hydroxide-silicate based activator solutions, to serve as binder in self curing concretes

GPC mixes were produced easily using tools and machinery similar to those of Conventional Concretes (CCs).

CONCLUDING REMARKS

GPC performs better in Rapid Migration Test (RMT) and Rapid Chloride Permeability Test (RCPT), compared to conventional concrete (CC)

Therefore, GPC is preferrable in constructions

Chloride Diffusion Coefficient (CDC) for GPC is lower than CC

Therefore, de-passivation time required (to initiate corrosion) for embedded steel reinforcement is higher

CONCLUDING REMARKS

GPCs

- **can be used structural grade concretes**

- **have lower**
  Carbon Footprint
  'Embodied Energy'
  'Embodied CO_2 Emission'

Possess longer service life

Nomenclatures of Amorphous alumino-silicates

(1) Soil cements [Glukhovsky, 1965]
(2) Inorganic polymer [van Wazer, 1970]
(3) Geolymers [Davidovits, 1978]
(4) Mineral Polymers [Davidovits, 1980]
(5) Geocement [Krivenko, 1994]
(6) Low-temperature aluminosilicate glass [Rahier, 1996]
(7) Alkali-activated cement [Roy, 1999]

Nomenclatures of Amorphous alumino-silicates

(8) Inorganic polymer glasses [Rahier, 2003]
(9) Alkali ash material [Rostami, 2003]
(10) Chemically Bonded Ceramics [Škvára, 2005]
(11) Alkali-bonded ceramic [Mallicoat, 2005]
(12) Hydroceramic [Bao, 2005]
(13) Inorganic polymer concrete [Sofi, 2007]
(14) Alkali-activated binders [Torgal, 2008]
(15) Alkali Activated Aluminosilicate [Provis, 2009]

CSIR-SERC

Dr Ambily P S

Ultra-High-Performance Geopolymer Concretes with alternates to conventional sand and stone aggregates

Structural engineering aspects of GPCs

Characterization of Indian Fly Ash from the Perspective of its suitability for Alkali Activation

The India Cements Ltd

F- Type Fly Ash Based Geopolymer Concrete

VNR Vignana Jyothi Institute of Engineering & Technology, Hyderabad

Strength Assessment of Geopolymer Concrete Slender Columns

(Thiagarajar College of Engineering, Madurai

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Behavior of Fly Ash based GPC Exposed to Elevated Temperatures
M. S Sudarshan & R. V Ranganath (R& D Civil Aid Technoclinic Pvt. Ltd)

Fly ash based Geopolymer Concrete- Durability studies and Behavior of Beams and Columns *Nirma University, Ahmedabad*

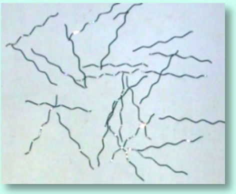
Studies on Strength and Behaviour of Steel Fibre Reinforced Geopolymer Concrete Structural Elements

Investigations carried by :Dr. N.Ganesan
:Dr. P.V.Indira
:Dr. Anjana Santhakumar

Department of Civil Engineering
NATIONAL INSTITUTE OF TECHNOLOGY CALICUT, KERALA, INDIA

Materials and Mix proportions

Materials for M40 grade GPC	Quantity (kg/m^3)
Coarse aggregate (max 12.5 mm)	1092
Fine aggregate	588
Fly ash	514
Sodium silicate solution	147
Sodium hydroxide solution (14 M)	59
Extra water	35
Super plasticizer	6.60

Type of fibre	 Crimped steel fibres
Length (mm)	30
Diameter (mm)	0.45
Aspect ratio	66
Ultimate tensile strength (MPa)	800

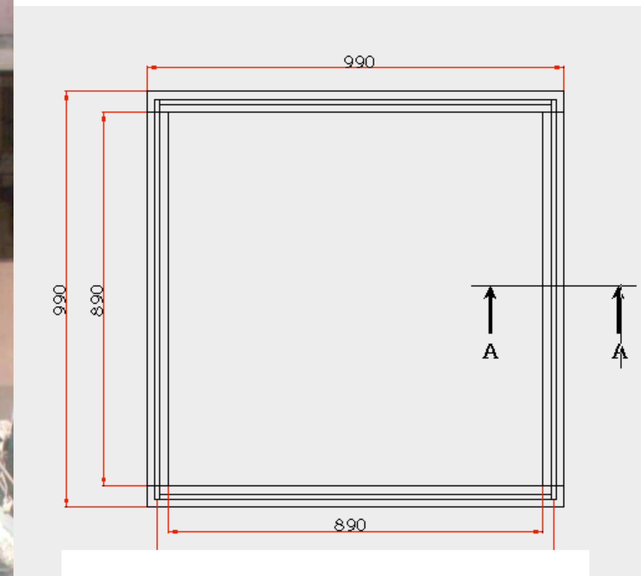
Durability Characteristics

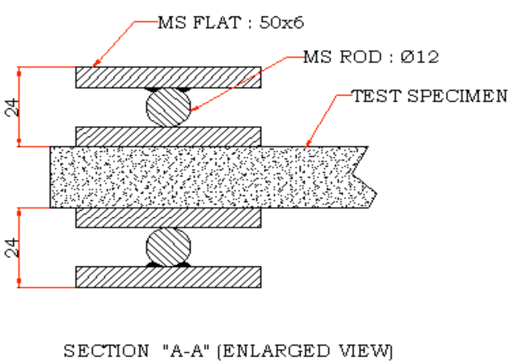
Properties		CC	GPC
Water permeability (cm/sec)		5.556×10^{-10}	2.777×10^{-10}
Chloride ion permeability		Very low	Very low
Loss in thickness(mm)		1.14	0.746
water absorption (%)		1.22	1.6
Sorptivity(mm/min$^{0.5}$)		0.127	0.097
Marine Attack	Change in mass (%)	9.39	5.69
	Loss in Compressive strength (%)	53.70	20.42
Sulphuric Acid Attack	Change in mass (%)	1.63	1.30
	Loss in Compressive strength (%)	29.54	17.52

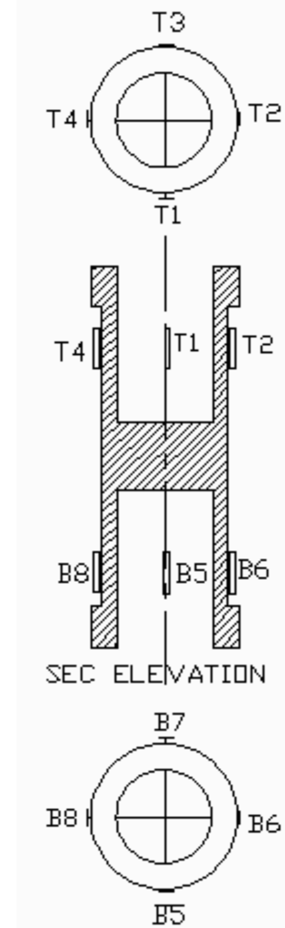

CONSTRUCTION OF ADDITIONAL FOUR
CLASS ROOMS AT KV-CLRI USING
CSIR-SERC TECHNOLOGIES
TECHNOLOGIES ADOPTED :
FLY ASH CONCRETE
SELF COMPACTING CONCRETE
EXPANDED POLYSTYRENE WALL PANELS
GEO POLYMER BRICKS
LIGHT WEIGHT FOAM BLOCKS
FLY ASH BRICKS
BUILT-UP AREA : 2860 sq.ft.
PROJECT COST : Rs.33 Lakhs.
PROJECT DURATION : 3 Months.
CSIR-INDIA
CSIR–SERC
ENGINEERING SUSTAINABLE STRUCTURES
CSIR –STRUCTURAL ENGINEERING RESEARCH CENTRE
TARAMANI CHENNAI -600113

GPC blocks for buildings

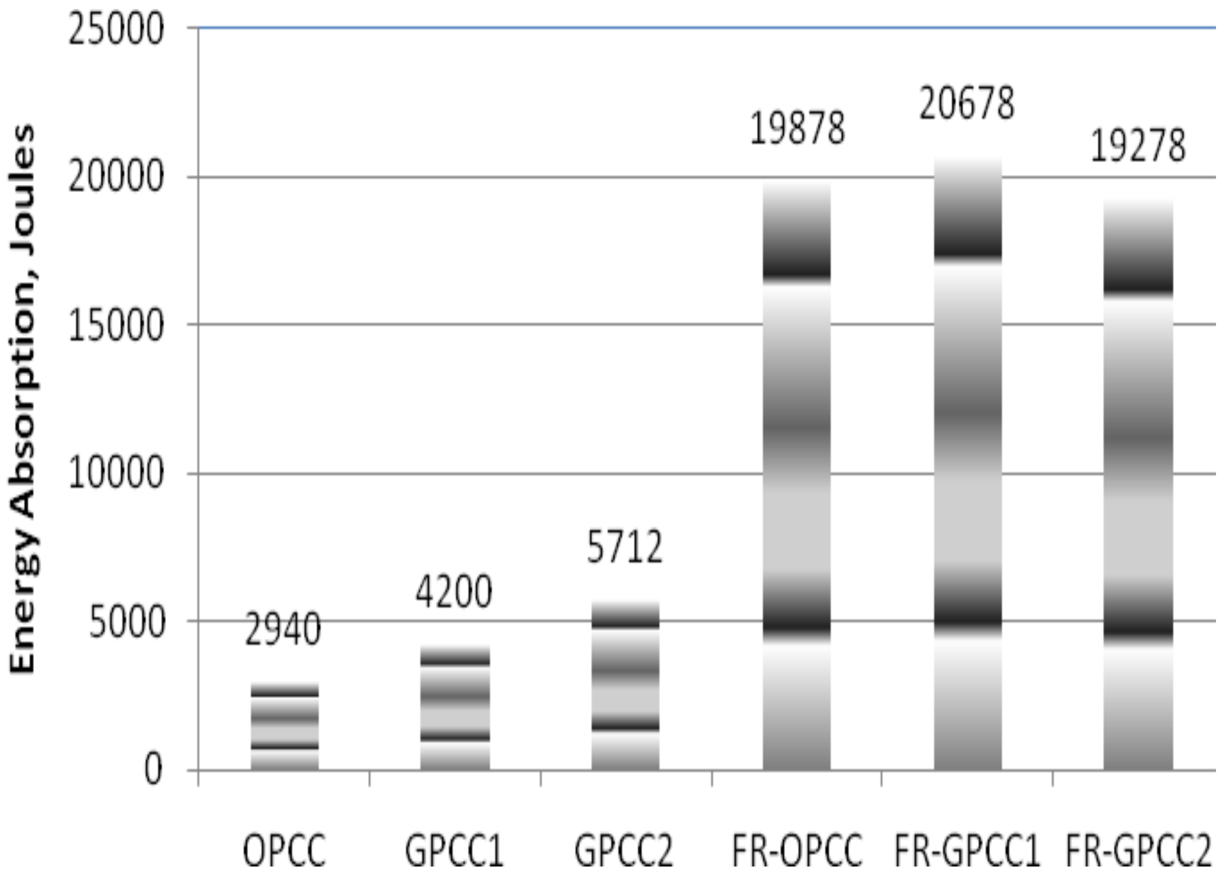
Experimental Set up for Impact Test



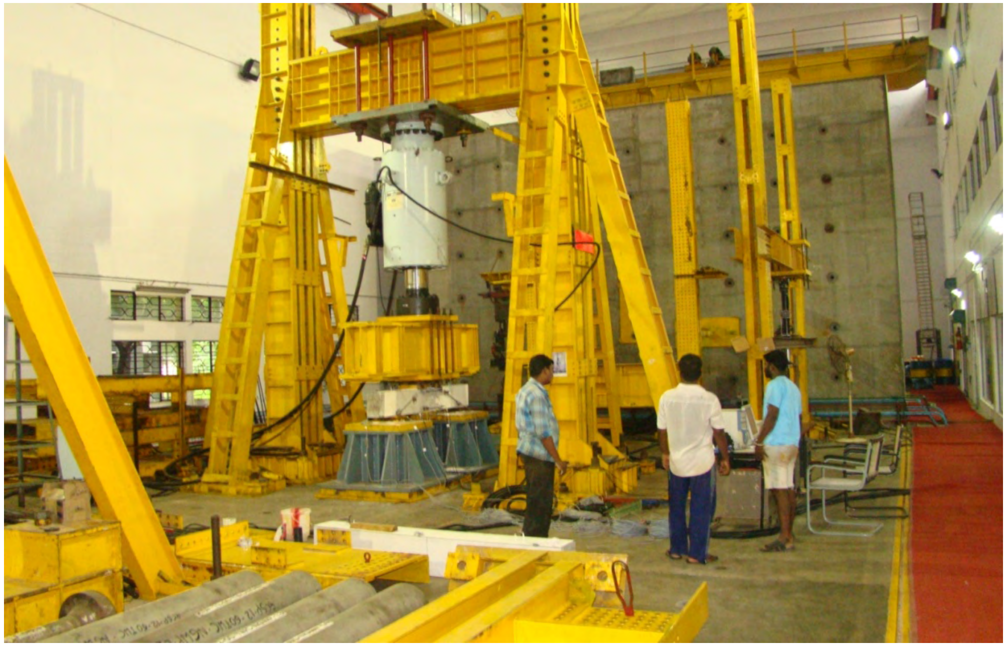


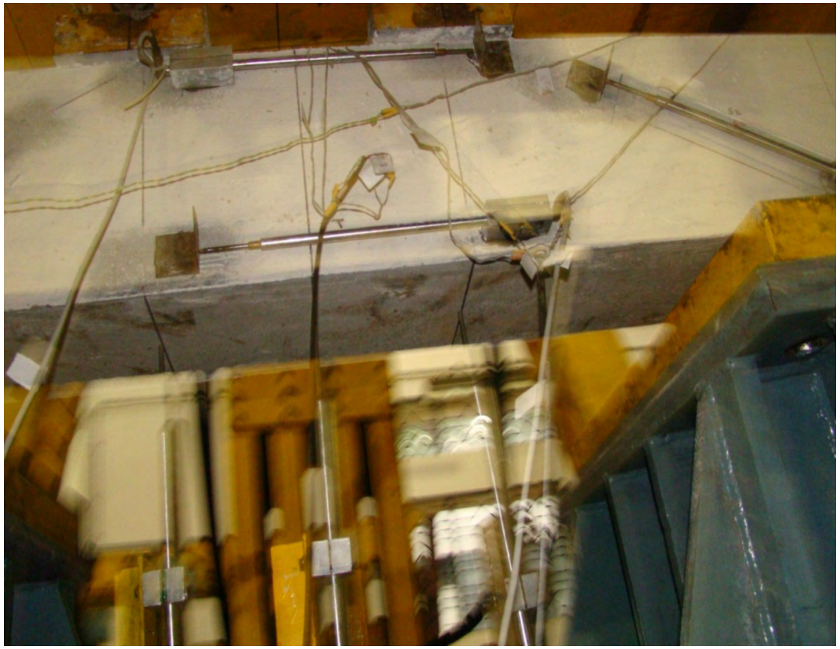


Energy absorption up to failure (perforation/scabbing) for different types of OPCC and GPCC Slabs

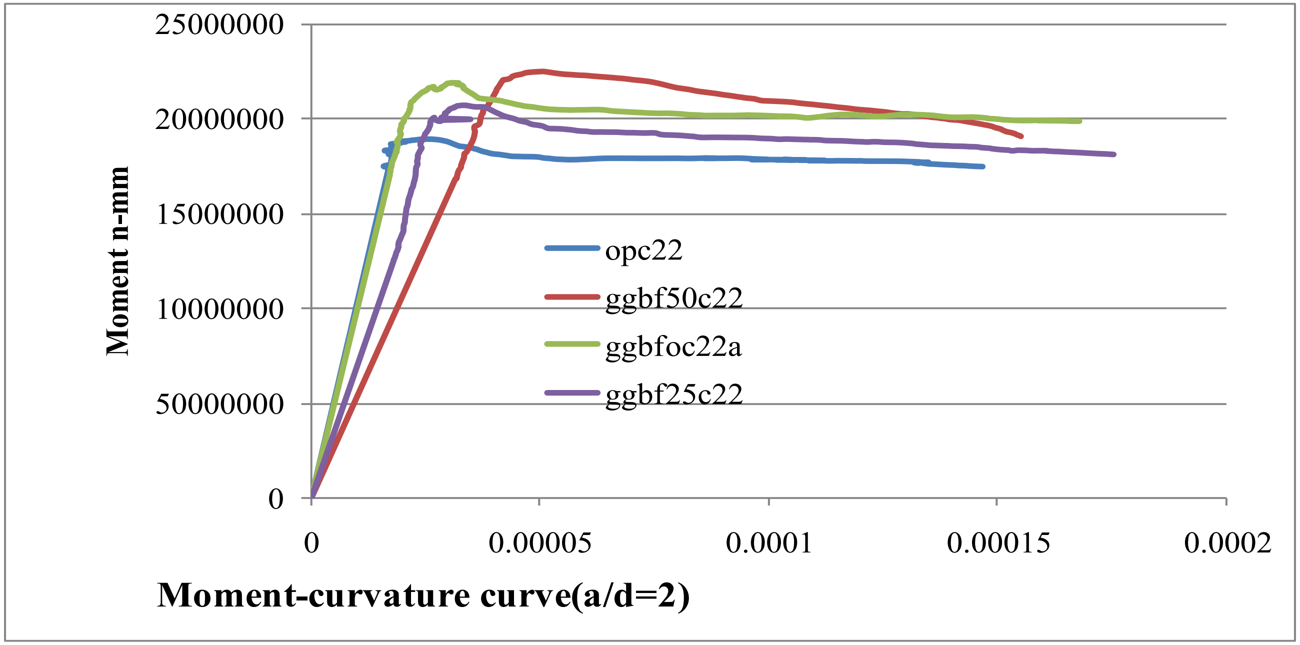


EXPERIMENTAL SET UP

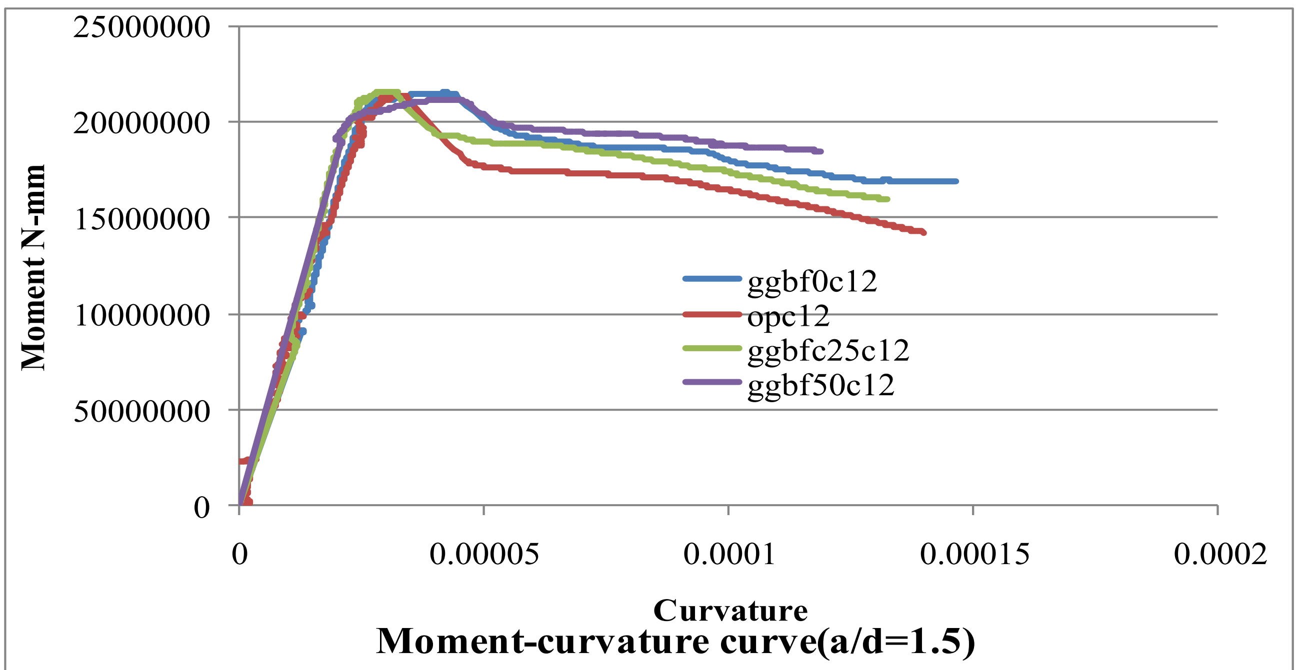




Shear Behaviour of Geopolymer Beams



Ultimate Load capacity of GPCC Beam was 15% more than OPCC



Crack pattern of GPCC Beam was similar to OPCC Beam

Geopolymer concrete with different activators

SAMPLES	BINDER: SAND: CA	COMPRESSIVE STRENGTH 7th DAY	28th DAY	DEGREE OF REACTIVITY	pH	% of Na_2O/ K_2O
SHSS	1:1.31:1.44	38.08	38.77	73.99	12.92	1.23/0.12
PHSS	1:1.31:1.44	25.27	28.82	56.02	12.78	0.84/0.47
SHPS	1:1.31:1.44	40.12	47.39	84.25	12.99	0.54/0.70
PHPS	1:1.31:1.44	43.59	47.32	83.66	12.96	0.35/1.19

SHPS, PHPS shows superior performance indicating Potassium silicate is a better activator.

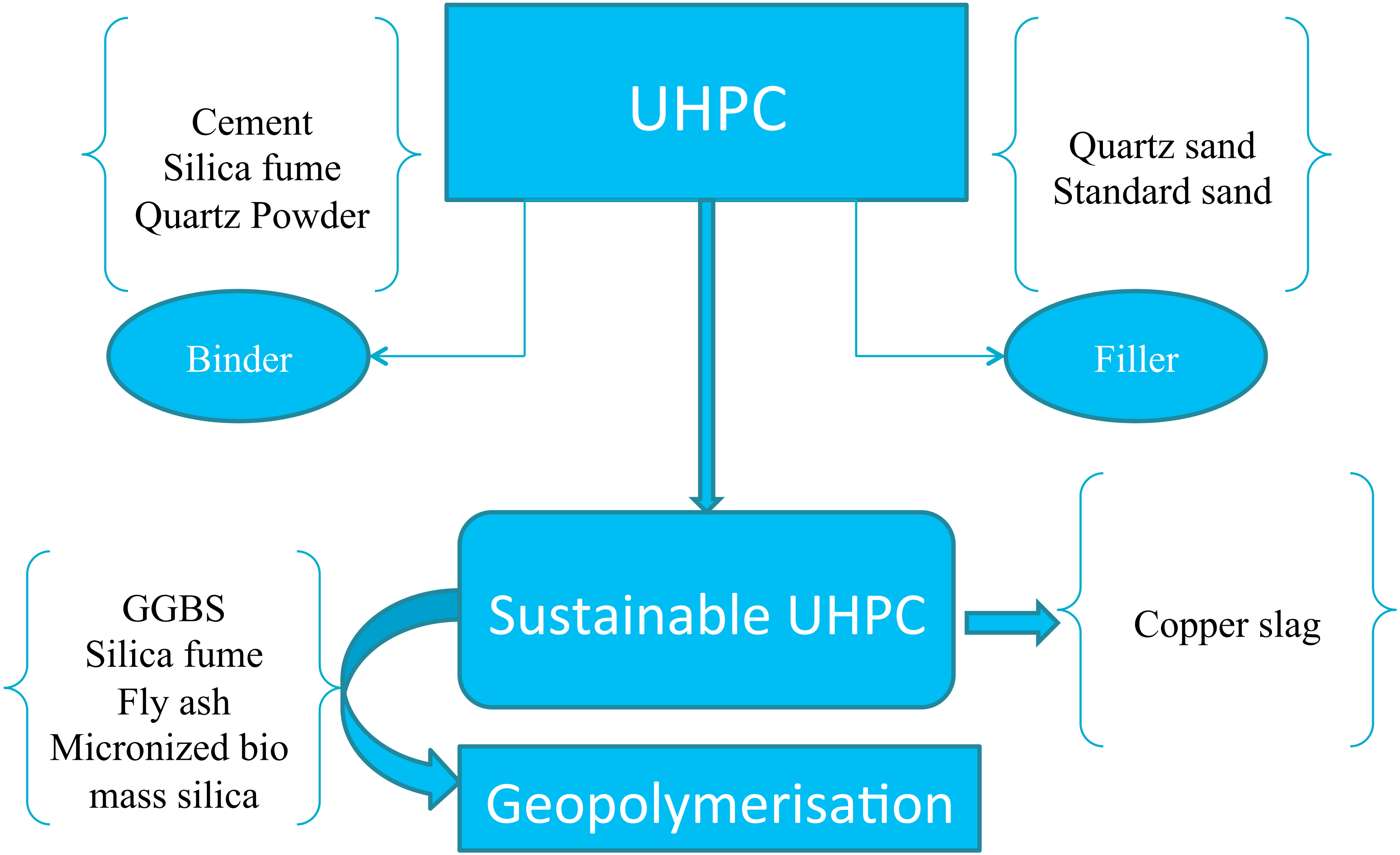
CONNECTION AT JOINTS AND TO THE CHANEL FIXED ON SHAKE TABLE




FILLING OF CUT OUT PORTIONS USING GEO-POLYMER CONCRETE



Methodology

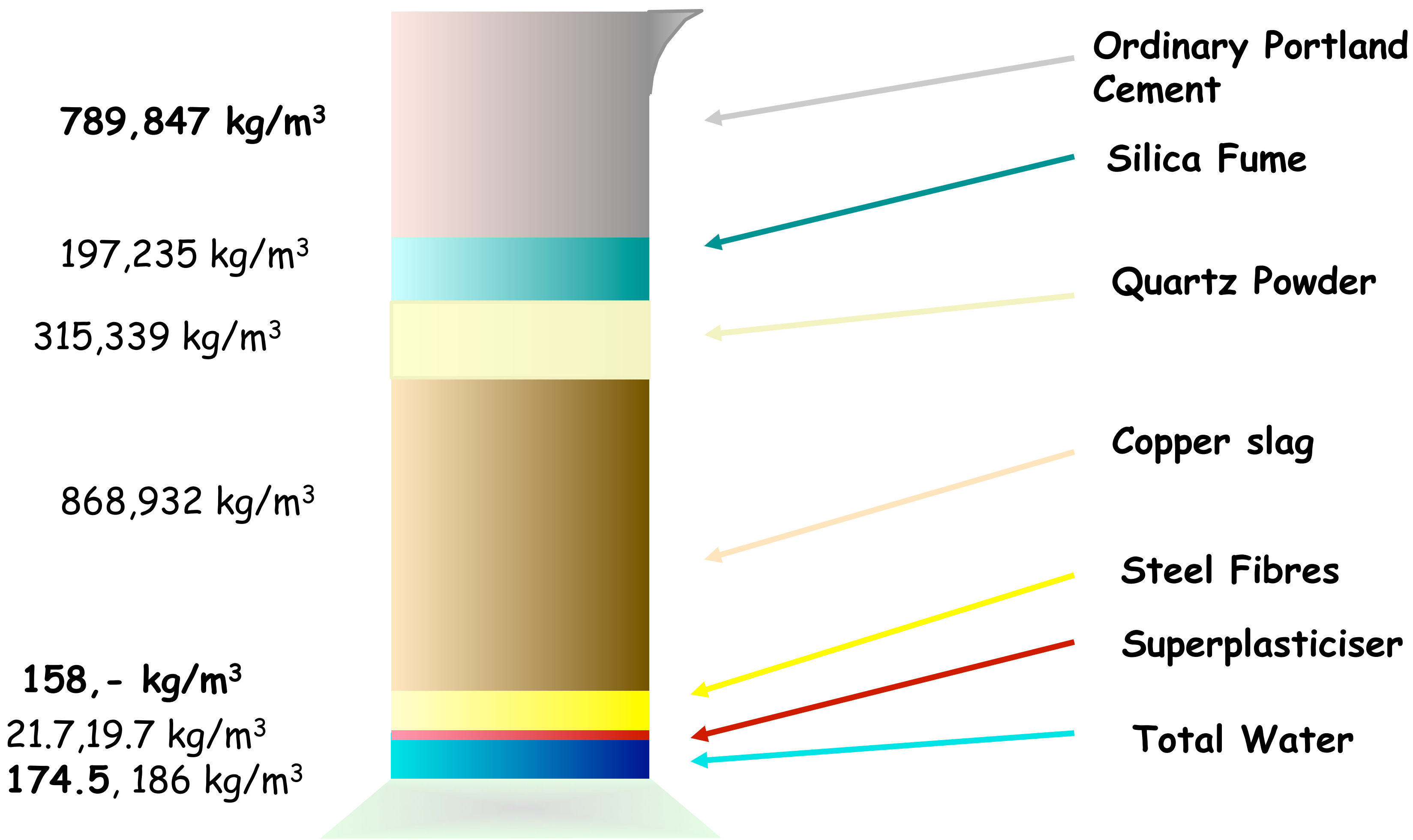


Development of alternate binder and filler system …

IDENTIFIED INGREDIENTS

- Ordinary Portland cement (53 grade OPC)
- Micronised biomass silica
- Quartz powder
- Silica fume
- Fly ash
- Ground granulated blast furnace slag
- Standard sand (Ennore sand, as per IS:650)
- Quartz sand
- Copper slag
- Polyacrylic ester type super plasticizer
- Steel fibre
- Alkali Activator Solution made of
  - Sodium hydroxide flakes (SHf)/ Potassium hydroxide flakes (PHf)Sodium silicate solution (SSS)/Potassium silicate solution (PSS)
- Water

UHPC-CS Mix Design



No coarse aggregate

Eirich Mixer

Flowable UHPC mix

Mixing of UHPC

Properties of Finalised UHPGPC Mixes

	Without fibre	With fibre			
Mix ID	UG11	UG7	UG12	UG13	UG14
Fresh Density (kg/m^3)	2394	2507	2513	2571	2501
Flow (%)	132	125	113	103	107
Compressive strength, fc(MPa)					
1 day (fc_1)	59	59	60	66	62
7 day (fc_7)	87	97	101	125	116
14 day (fc_{14})	111	114	128	152	142
28day (fc_{28})	124	130	144	175	154
Rate of compressive strength development (%)					
fc_1/fc_{28}	48	45	42	38	40
fc_7/fc_{28}	70	75	70	71	75
fc_{14}/fc_{28}	90	88	89	87	92
% increase in fc_{28} with fibre	0	5	16	41	25
Flexural strength, fb(MPa)					
28 day	9.1	10.3	12.1	13.5	12.15
% increase in fb (with fibre)	0	13	33	48	34

UHPC-Geopolymer and Copper Slag…

Properties of UHGPC-CS Mixes

Mix ID	UEF	UE	UCF	UC
Fresh Density(kg/m³)	2530	2370	2550	2670
Flow (%)	120	130	135	Full Flow
Compressive strength(MPa)				
1 day	64	56	68.6	68.5
7 days	112.0	76.2	136.3	78.8
14 days	127.2	81.5	149.9	89.6
28 days	151.5	101	164.9	106
Rate of compressive strength development (%)				
fc_1/fc_{28}	42	55	42	65
fc_7/fc_{28}	74	75	83	74
fc_{14}/fc_{28}	84	81	91	85
% increase in fc_{28} with fibre	50	-	55	-
Flexural strength (MPa)				
28 day	11.6	7	10	6.9
% increase in fb (with fibre)	65	-	45	-

Ultra High performance concrete						
Mix ID	EE	ECo2e	Cost	Strength	EE / Strength	ECO2e / Strength
UHPC	7779	994	31223	191	40.7	5.2
UHPC-CS	7796	999	31223	162	48.1	6.2
UHPGPC	7936	869	36188	154	51.5	5.6
Conventional Concrete						
CC	2486	484	5429	43	58	11.3
GPC	1591	272	5212	45	35	6.0

THANK YOU