Ecologically Sustainable Material for Structural Strengthening, Corrosion and Fire Protection of Structures

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Background to Developments

- SHU developed geopolymer formulations for past 15 years
- Intent to develop carbon fibre with dual function corrosion protection & structural strengthening by patent application 2002
- 2010 commissioned PhD study
- By 2011 first results show success achieving EN/ NACE standard ICCP criteria with carbon fibre and geopolymer as composite material
- Use of geopolymer adds features to the end product
- First publication in 3rd ICCRRR in September 2012
- Second publication in ISRN Corrosion within 2012
- PhD due to be completed June 2013

Definition of Geopolymer

- Term first applied by Prof Joseph Davidovits in the 1970s
- Originating from “soil cements” in the 1950s in the former Soviet Union
- Broadly known as alkali-activated cement binders
- Attention increased due to desire for alternatives to ordinary portland cements for environmental reasons

Geopolymer Attributes

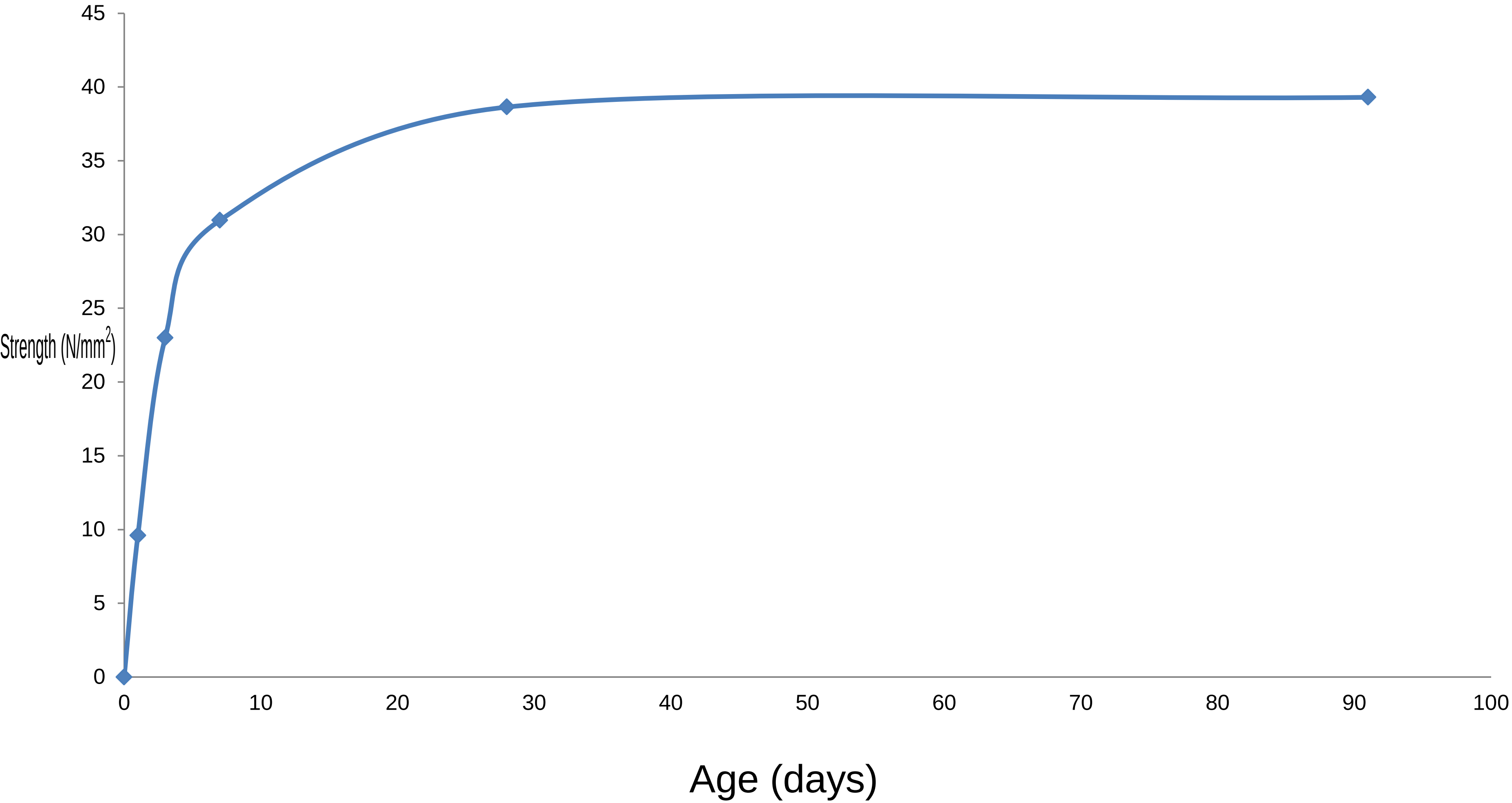
- Manufactured as a sustainable material
  - Uses recycled materials from power generation & mining
  - Emits >80% less CO_2 than ordinary portland cements (OPC)
  - Lower energy consumption than OPC (cold formed cf 1400C (2550 F))
  - No water needed

- Key features
  - Build AND repair AND protection material
  - Low resistivity (2-3kohm.cm)
  - Comparable moisture penetration to OPC concretes (ca. 5%)
  - High compressive strength (30-80MPa (4,350 - 11,600 psi) - can be tailored)
  - Excellent bond strength (3.0-3.5MPa (435 - 510 psi))
  - Fire resistant (1100C (2012F) for over 4 hours)

Compressive Strength

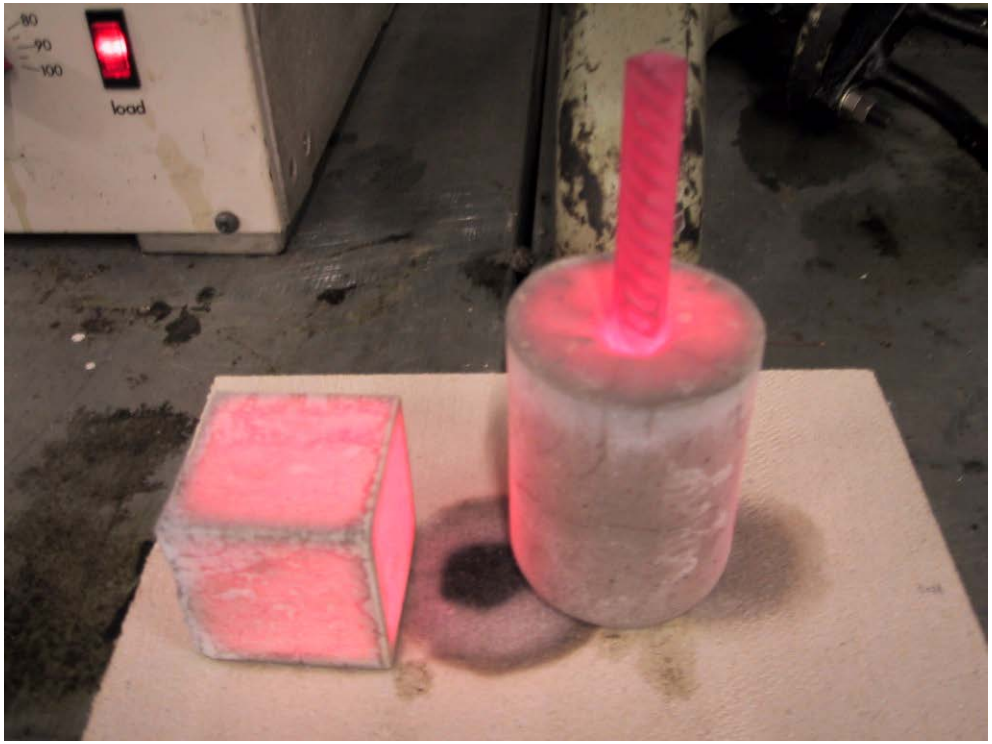
- Can be tailored by adjustments to cement formulation
- Laboratory tests performed to BS1881:116:1983
- Compositions designed to provide 28 day strengths from 20 N/mm^2 to 80 N/mm^2 (2,900 – 11,600 psi)
- Literature evidence from real constructions show increase in strength over >30 year period suggesting continued geopolymerisation occurs over time
- Geopolymer fire plug panels carried in excess of the permissible $5kN/m^2$ (104) without distress

Typical strength gain profile



Fire Resistance

- Known refractory material
- ASTM C24 (Ceram) test of reinforced lintels independent assessment
- Demonstrates no change in hardened geopolymer form at 1100C (2012F) for 4 hour period
- Likely to withstand ca 1900C (3450F)



Absorption/Permeability

Two test methods were used:

1. BS1881:122:1983 and ASTM C642-90. Absorption measured after oven drying and soaking of test samples
2. Sorptivity test measured the capillary rise water absorption through the contact surface with water of an oven dry sample.

- A range of geopolymer formulations were tested and compared with compositions of OPC concrete with water/cement of 0.5
- Samples were cured in air, 20 deg C (68F), 65% RH

Absorption/Permeability

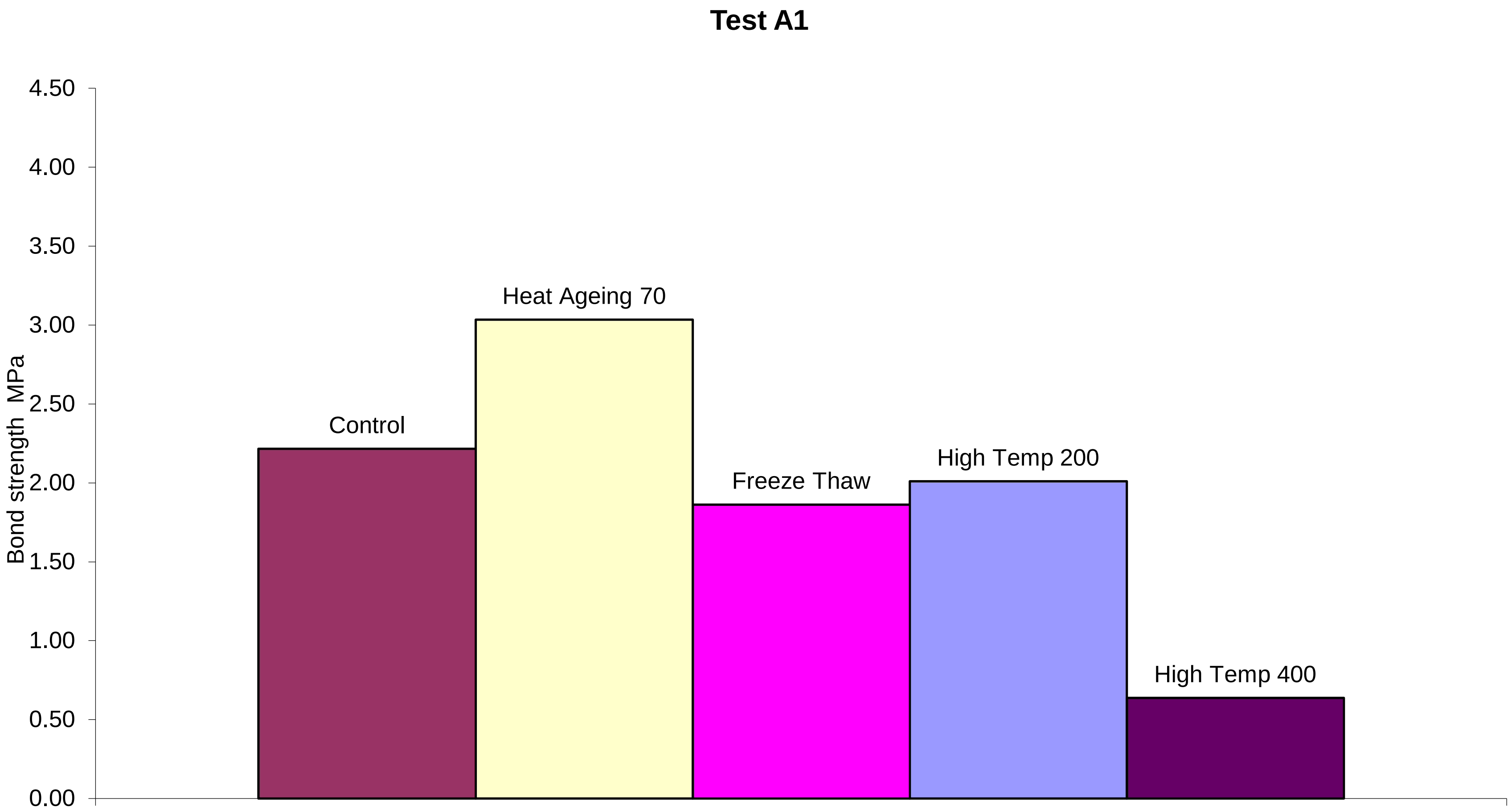
- The absorption of the geopolymer compositions was between 5.2% and 9.8%.
- The absorption values of the concrete samples were between 8.5% and 12.4%.
- The permeability of the geopolymers therefore compares with good quality concrete.

Bond Tests

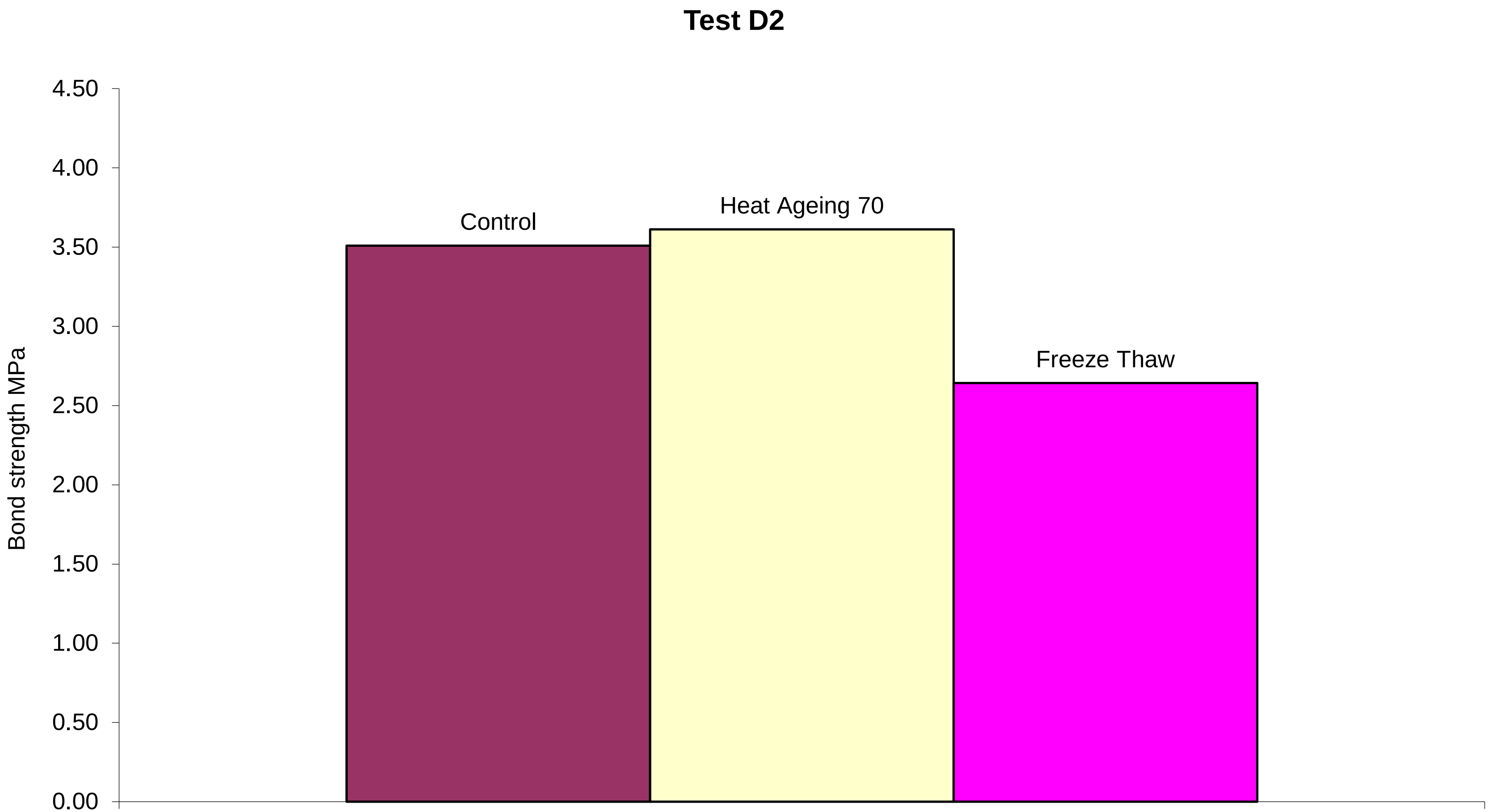
- Samples prepared to compare geopolymer formulations with epoxy bond to hardened concrete
- Coupled to freeze-thaw cycling and heat resistance tests

Bond test samples (after freeze-thaw cycles)

Bond Strength (Epoxy 1)



Bond Strength (Geopolymer)



How is it made?

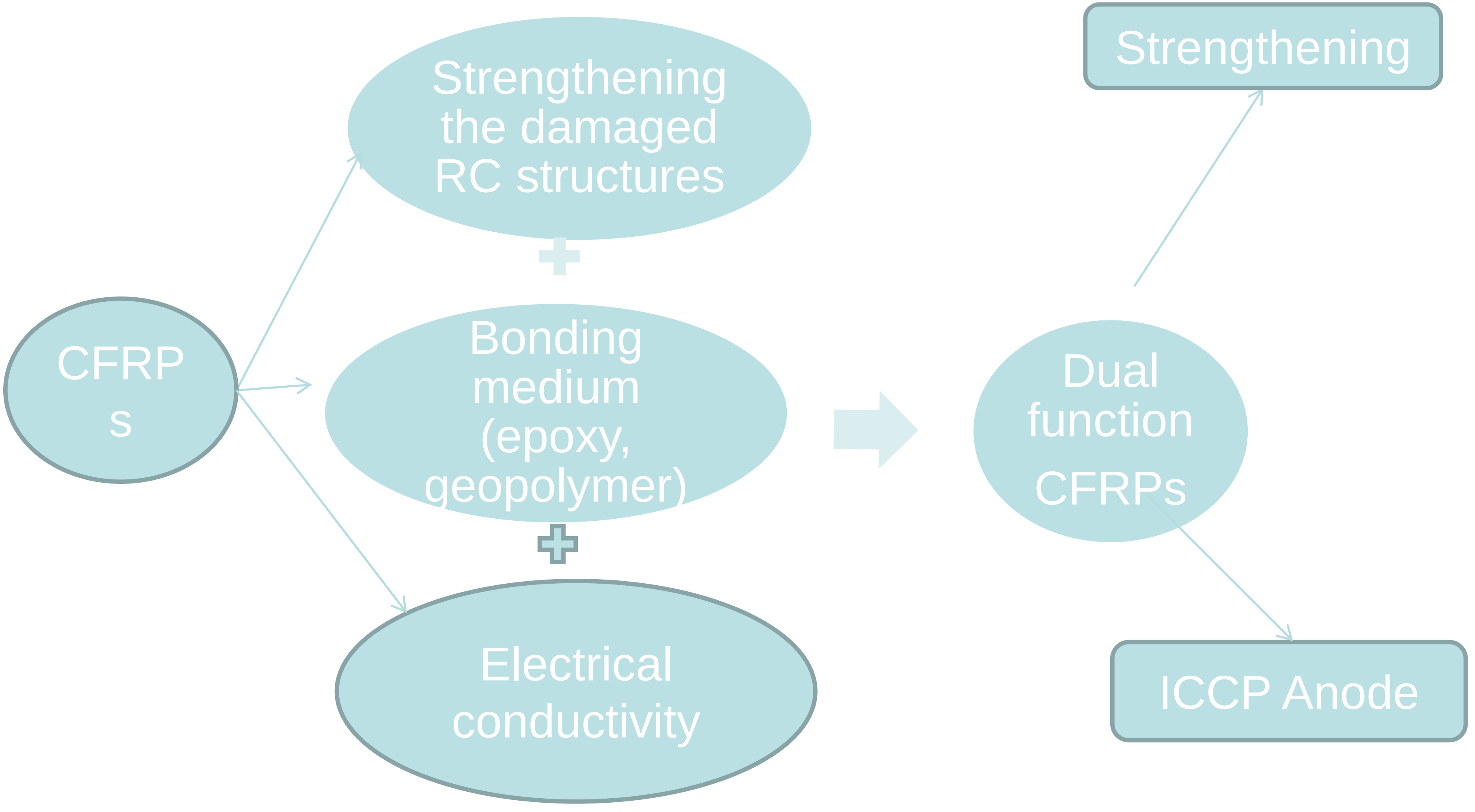
- Ambient mix of recycled materials to form geopolymer cement (part 1)
- Ambient mix of alkaline blend of silicates for liquid (part 2)
- Alkaline solution dissolves silicon and aluminum ions
- Temperature triggering by addition of the alkaline activation liquid to polymerize to a solid form in oxygen bonded tetrahedra balanced by cation bonding (Ca, Na, etc)
- Non-crystalline structure (largely, amorphous)
- Removes water in the process

Dual Functional Strengthening Anodes

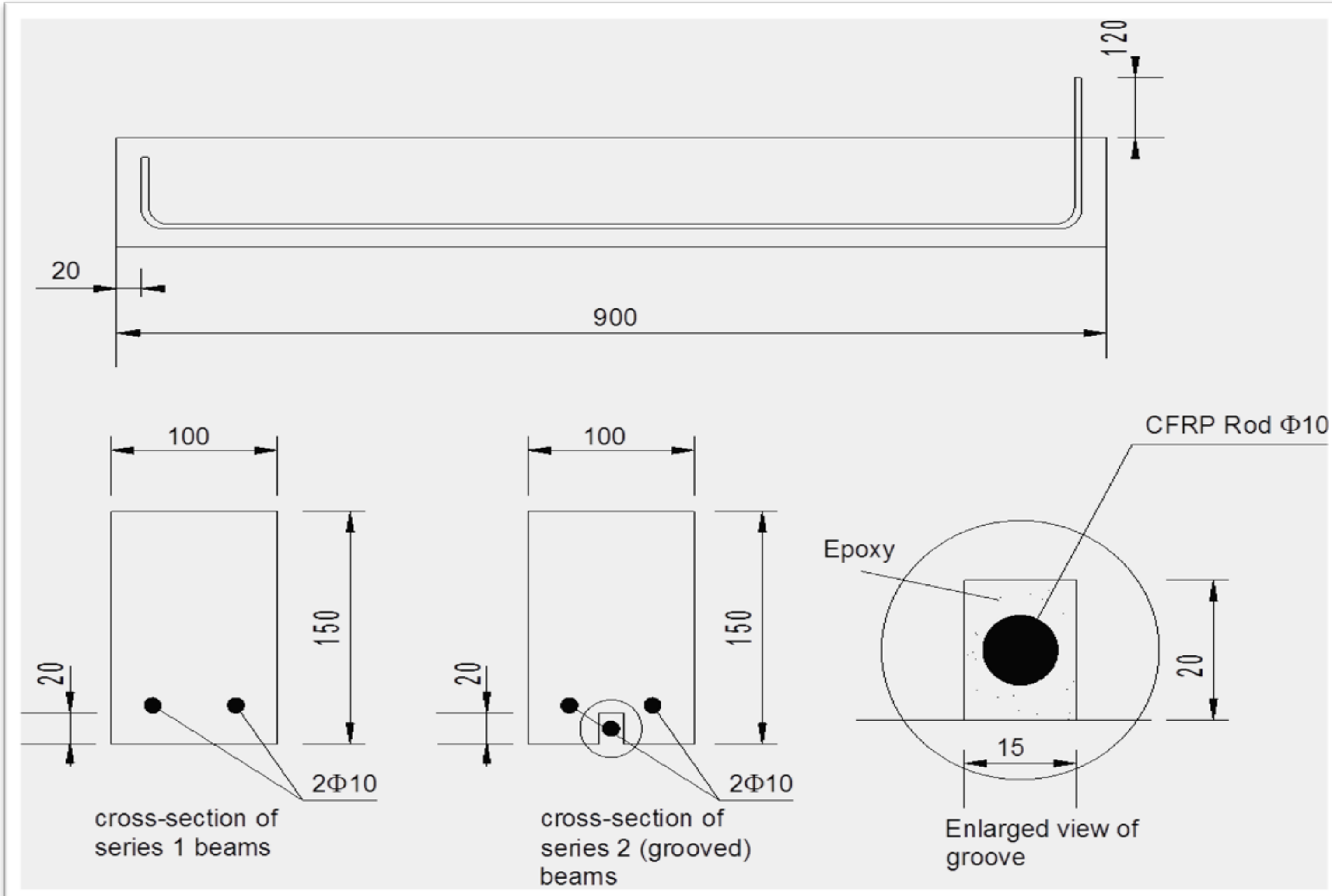
Experiment - Dual Functional Strengthening Anode

- To investigate the effectiveness of CFRPs to work as an ICCP anode with no impact on normal strengthening characteristics.
- Two bonding mediums have been investigated:
  - Epoxy (commercial epoxy adhesive)
  - Geopolymer (alkali activated recycled binder material)
- 2 parameters have been used:
  - Structural parameters: load-deflection relationship and failure of beams under bending test.
  - Electrochemical parameters: distribution of protection current to reinforcing steel, ISO EN12696:2012 criteria compliance, anode capacity and durability.

Project Objectives



Detailed dimensions of beam specimens

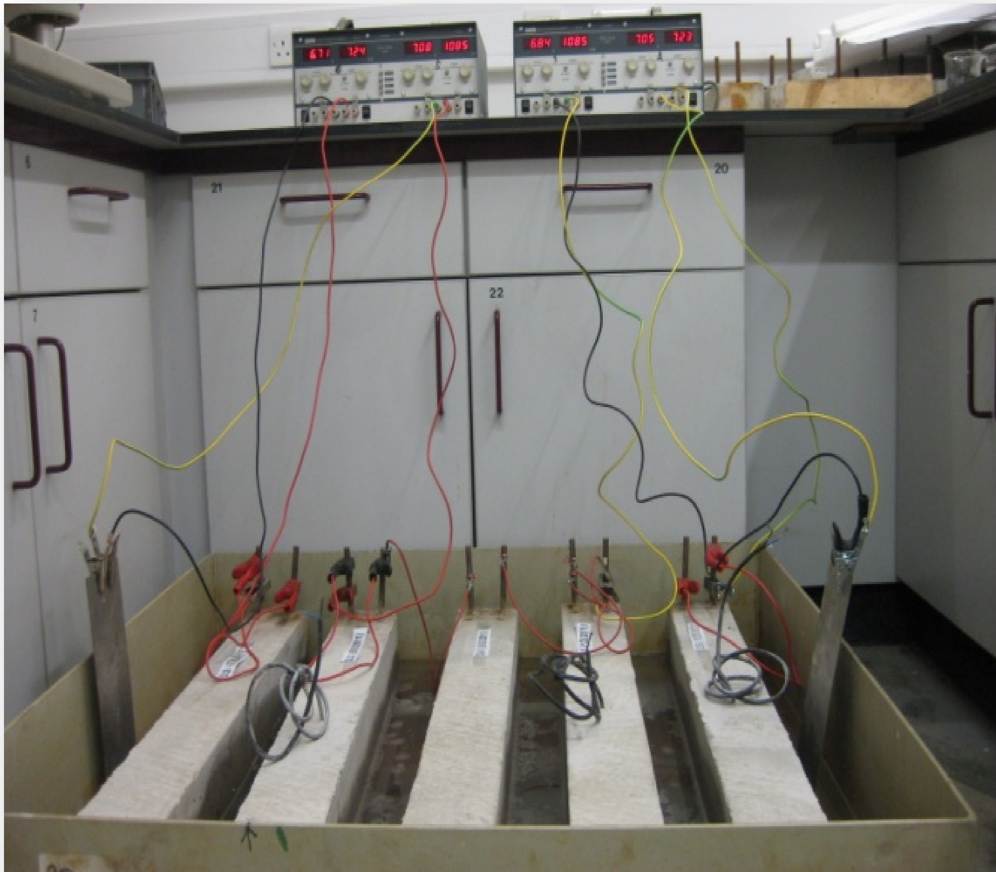


Application of Carbon Fibre Reinforced Polymers

Series of beams tested

Series	ID	Degree of pre corrosion (%)	Description
1. Dual function CF fabric	1.1	0	control
	1.2	2.5	not strengthened with CFRP, no cathodic protection (CP)
	1.3	2.5	strengthened with CFRP fabric in Resin (Epoxy+CFRP fabric)
	1.4	2.5	strengthened with CFRP fabric in Resin (Epoxy+CFRP fabric)
	1.5	2.5	strengthened with CFRP fabric in Resin (Epoxy+CFRP fabric)+CP (CFRPF1)
	1.6	2.5	strengthened with CFRP fabric in Resin (Epoxy+CFRP fabric)+CP (CFRPF2)
2. Dual function CF rod	2.1	0	control
	2.2	2.5	not strengthened with CFRP, no CP
	2.3	2.5	strengthened with CFRP Rod + (Geopolymer +chopped CFRPs fabric)
	2.4	2.5	strengthened with CFRP Rod + (Geopolymer +chopped CFRPs fabric)
	2.5	2.5	strengthened with CFRP Rod + (Geopolymer +chopped CFRPs fabric)+CP (CFRPR1
	2.6	2.5	strengthened with CFRP Rod + (Geopolymer +chopped CFRPs fabric)+CP (CFRPR2

Accelerating corrosion of reinforcing steel



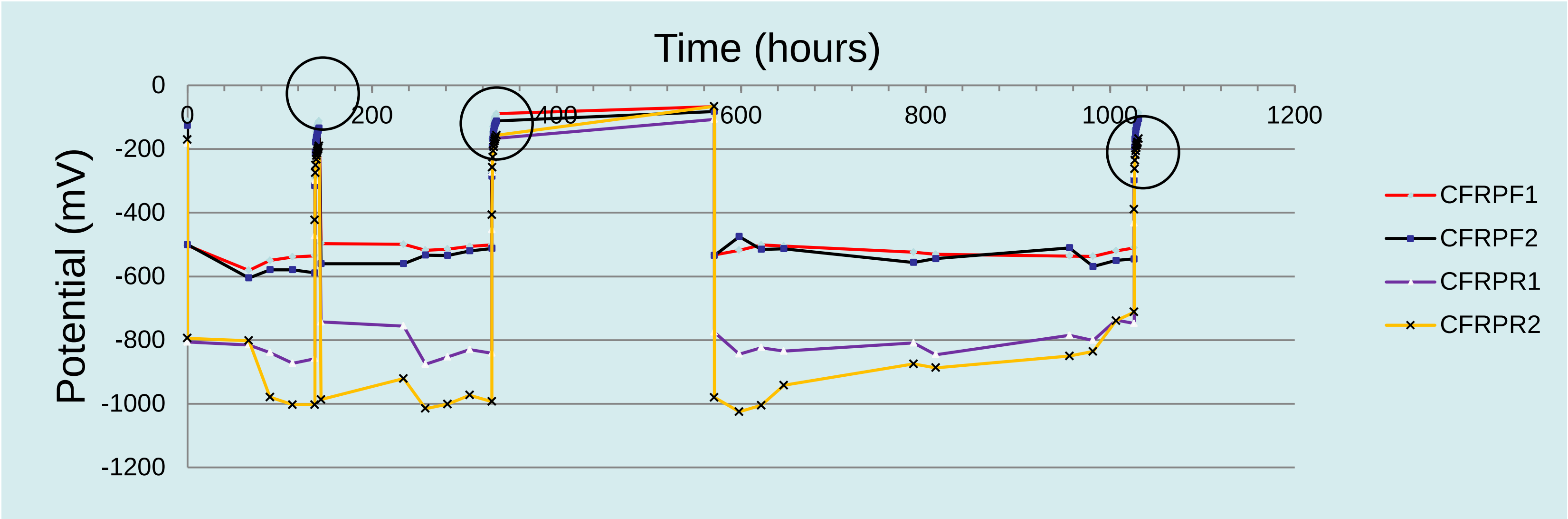
- Techniques: impressed anodic current, with aim to produce 'general corrosion’
- The target: 2.5% degree of corrosion
- A current density of $1mA/cm^2$ ($6mA/in^2$) was employed

Corroded reinforced concrete beams

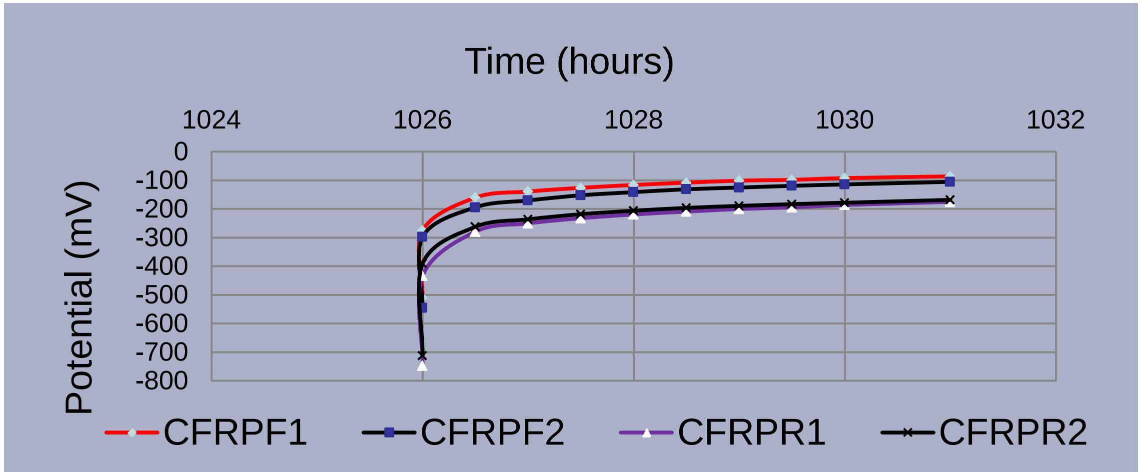
Application of ICCP

Applied currents:
10mA for CFRP fabric anode (eq. to 128.42mA/m^2 (107 mA/yd^2) steel)
5mA for CFRP rod anode (eq. to 64.21mA/m^2 (54 mA/yd^2) steel)

ICCP Assessment: Controllability and ISO compliance



Potential of steel during operation of ICCP



Potential decay of reinforcing steel in the third period

The potential decays >150mV after 4 hours (tested at 138, 330 and 1026 hours)

Based on ISO EN 12696:2012, this confirms protection has been achieved

Results and discussion

Visual monitoring

Yellow liquid deposit

A small number of gaseous yellow liquid deposits appeared on the surface of CFRP fabric of specimen ID 1.5 after **982.5 hours** of operation of the ICCP system

Analysis showed the deposits to be ~60% chloride.

The structural performance of dual functional CFRP anode

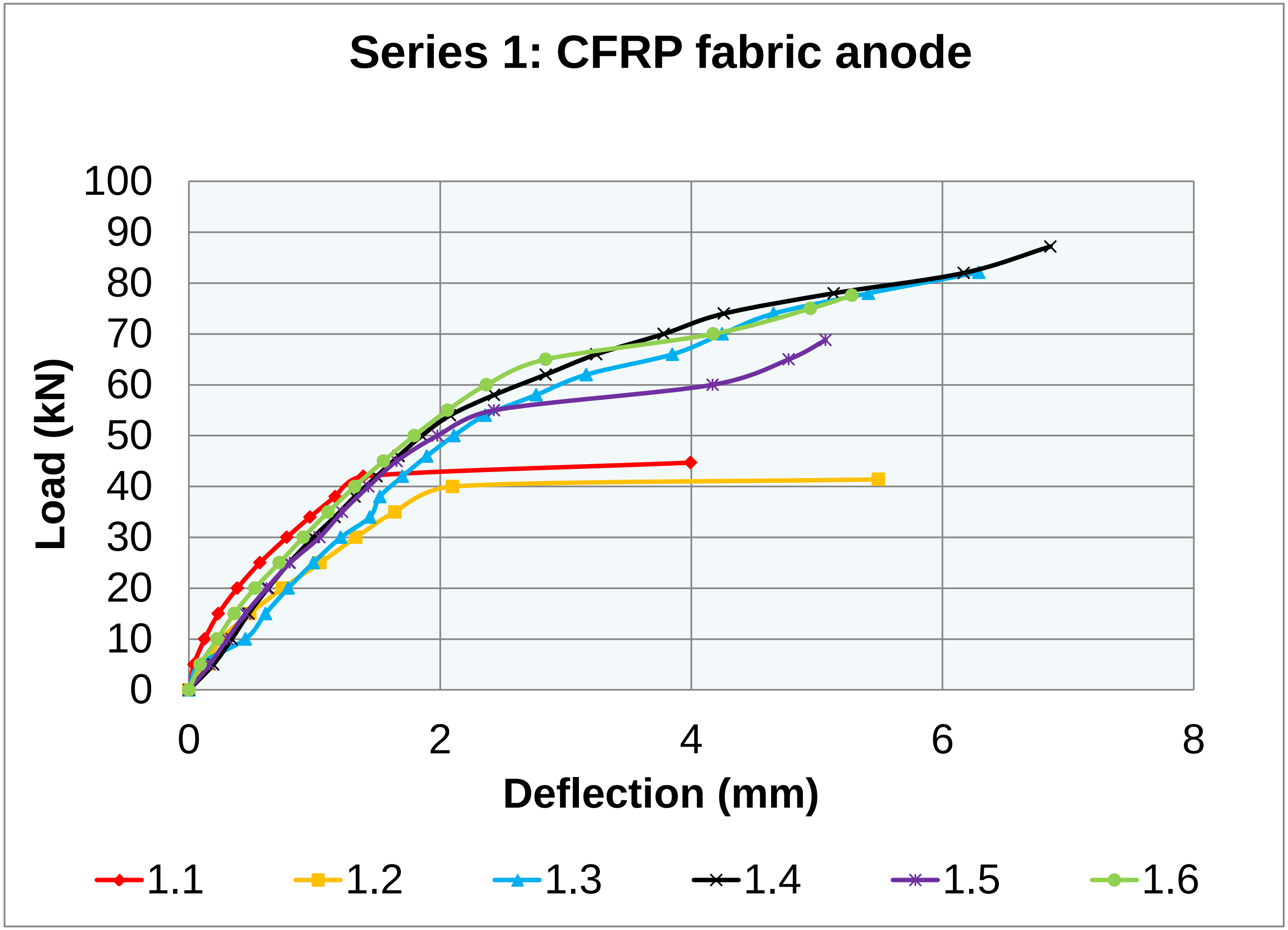
Bending test of dual functional CFRP fabric beams at ultimate load

The structural performance of dual functional CFRP anodes

CFRP fabrics - after testing
Failure in concrete

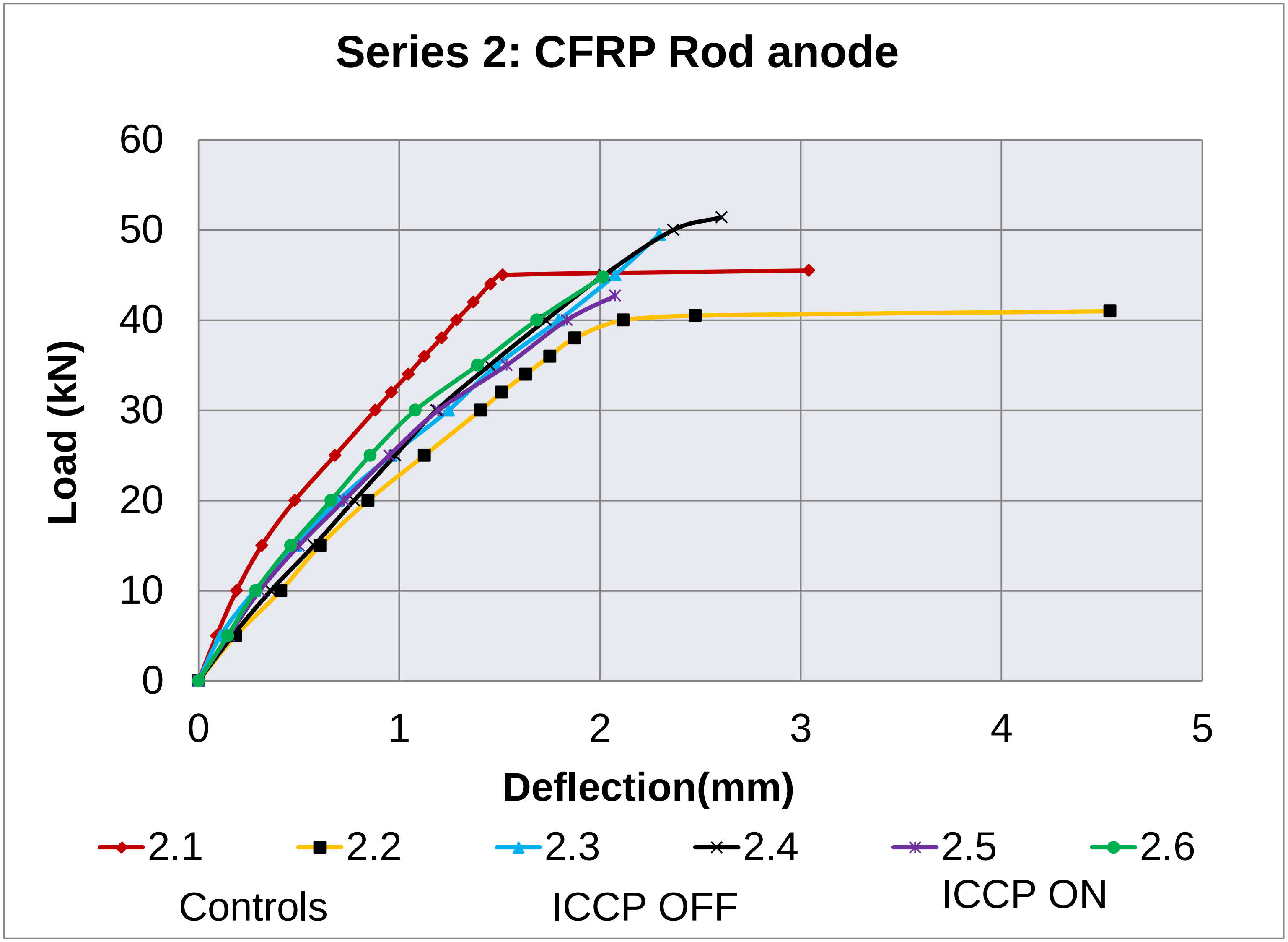
CFRP rod - after testing
Failure at rod:concrete interface

Load- deflection curves



Controls ICCP OFF ICCP ON

Load- deflection curves



Conclusions

- CFRPs can be used as impressed current cathodic protection (ICCP) anodes for reinforced concrete structures meeting the requirements of ISO EN 12696:2012 demonstrating that protection is being achieved.

- Output currents achieved also exceed normal ICCP operating levels with no loss of structural integrity.

- The geopolymer formulation extended with chopped carbon fibres is suitable for bonding CFRP to concrete and use as an anode.

- Composite of geopolymer anode with CFRP also has high fire resistance.

Conclusions cont'd

•CFRP fabric is capable of operating at very high current densities >128mA/m^2 of steel area with only a small loss of mechanical bonding while CFRP rod can operate at >64mA/m^2 of steel area without any signs of damage or bonding problems

•CFRP anodes can be used to strengthen corroded RC beams. They also increase the stiffness of beams and reduce their ultimate deflection

Dual functional use proven which with fire resistance exceeds objective solution planned for project as tri-functional performance

Future work & Fine tuning Development

•Further research is currently underway to improve the bond at the CFRP interface when employed as ICCP anodes.

In addition, enhancements to the bonding materials are being examined to optimize the bond strength of CFRPs to concrete.

•The current density for operating the ICCP anode is also subject to be further research and optimisation to prevent acid generation – at least $64mA/m^2$ ($54mA/yd^2$) at steel thought to be achievable

•Parallel site testing about to start for inclusion within PhD programme that will extend to long-term testing afterwards

Thank You for listening

We would be grateful for any questions you may have

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