Bioactive Bone Cements – Advantages and Limitations

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UNIVERSITY *of* LIMERICK

CABER

HEA

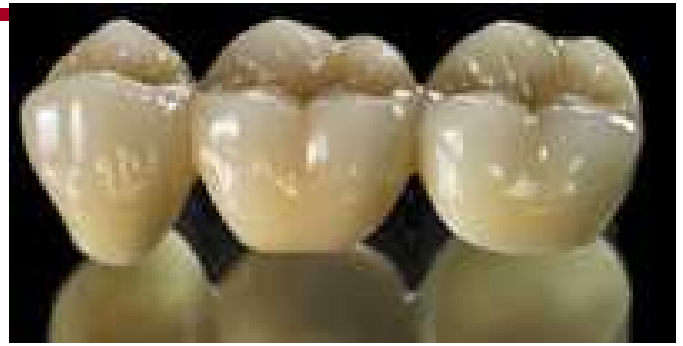
Higher Education Authority
An tÚdarás um Ard-Oideachas

MSSI

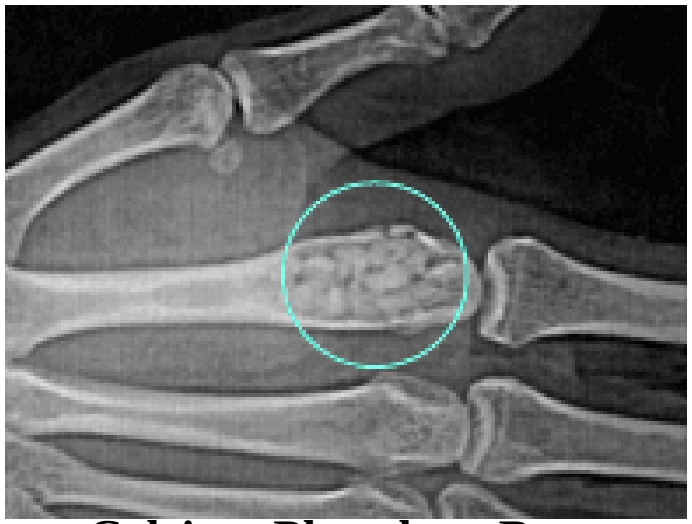
Ceramics for Biomedical Applications

Alumina on Alumina Hip Bearing

Various ceramic implants

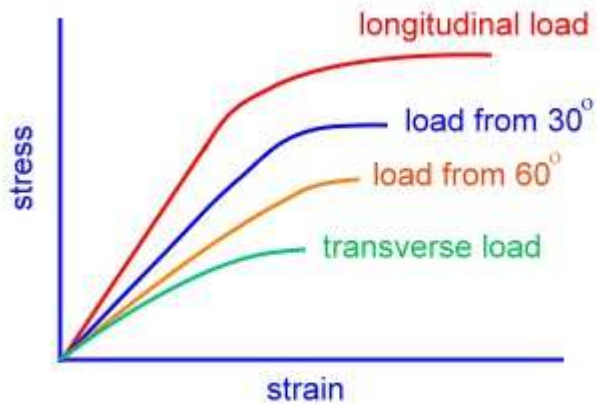


Dental Restoratives

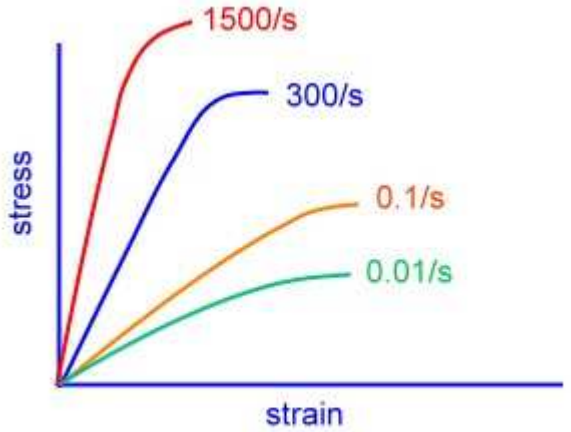


Calcium Phosphate Bone Substitute

Bone Mechanics



Anisotropic Behavior of the Bone



Rate Dependent Behavior

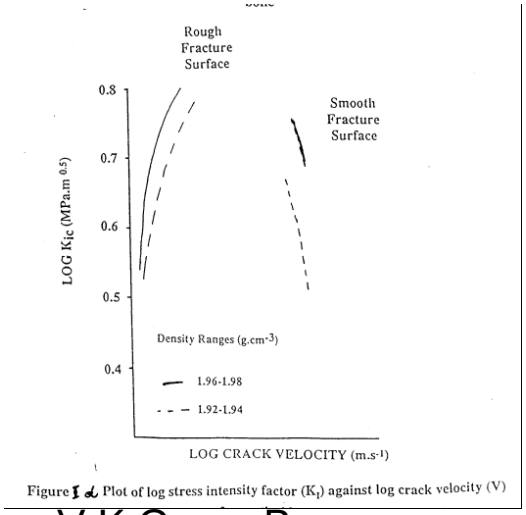


Figure 1d Plot of log stress intensity factor (K_I) against log crack velocity (V)

V-K Curve Bone

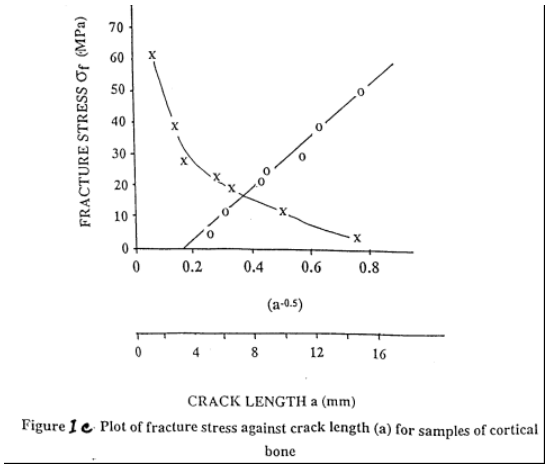
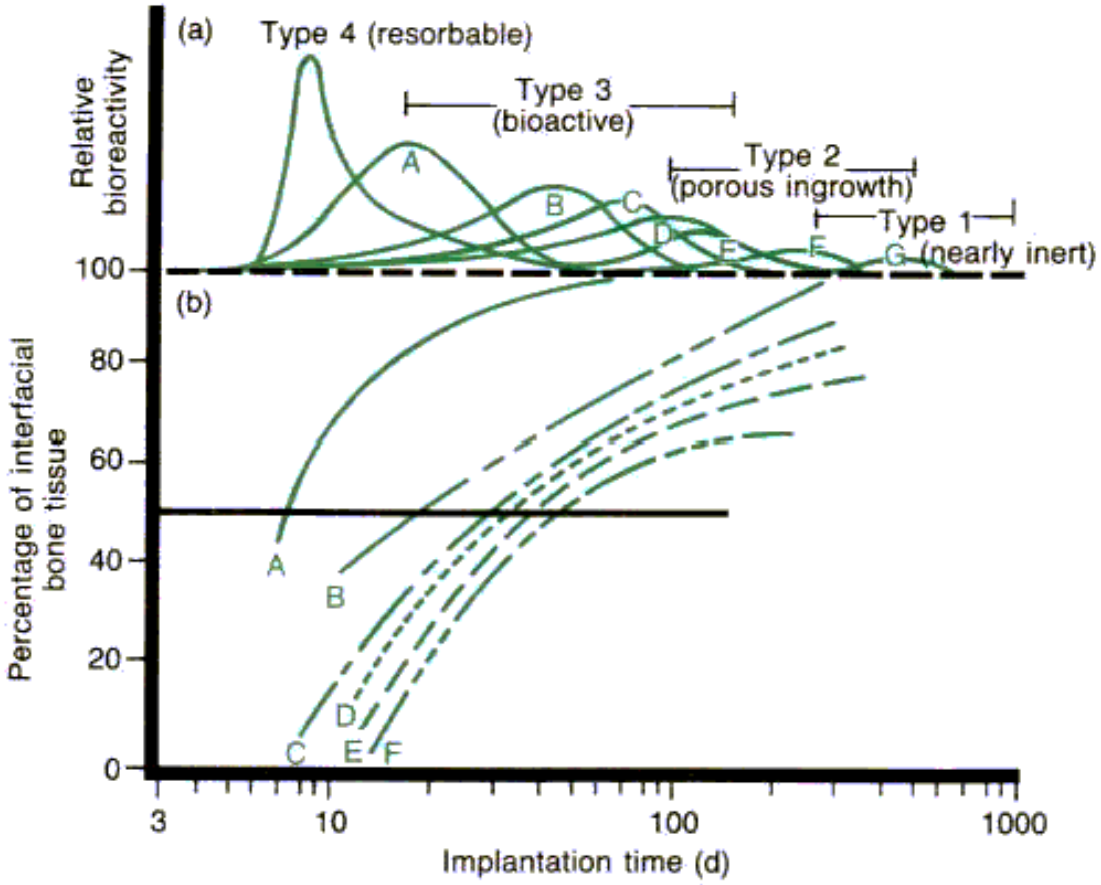


Figure 1e Plot of fracture stress against crack length (a) for samples of cortical bone

σ_f Vs Flaw Size - Bone

Ceramics of Implant Use



Bioactivity spectrum for various bioceramic implants, (A) Relative rate of bioreactivity, (B) Time dependence of formation of bone bonding at an implant interface. [1]

1. Hench, L J. Am. Ceram. Soc. 74 (7) 1487-510 (1991)

Bioactive Material

- ‘‘one which has been designed to induce specific biological activity’’ [2]
- “Bone bonding….. via a time-dependent, kinetic modification of the surface that occurs upon implantation the surface forms a biologically active hydroxycarbonate apatite (HCA) layer which provides the bonding interface with tissues[1]
- ‘‘.the essential requirement for a material to bond to living bone is the formation of bone-like apatite on its surface when implanted …..this in vivo apatite formation can be reproduced in a simulated body fluid (SBF) with ion concentrations nearly equal to those of human blood
- plasma.’[3]

1. Hench, L J. Am. Ceram. Soc. 74 (7) 1487-510 (1991)
2. ESB consensus conference of 1987.
3. Kokubo T, Takadama H. How useful is SBF in predicting in vivo bone bioactivity? Biomaterials 2006;27:2907–15.

“Can bioactivity be tested in vitro with SBF solution?”[4]

- “Both serum and SBF are supersaturated towards apatite crystals….. system is metastable and will eventually become thermodynamically stable by forming apatite crystals”

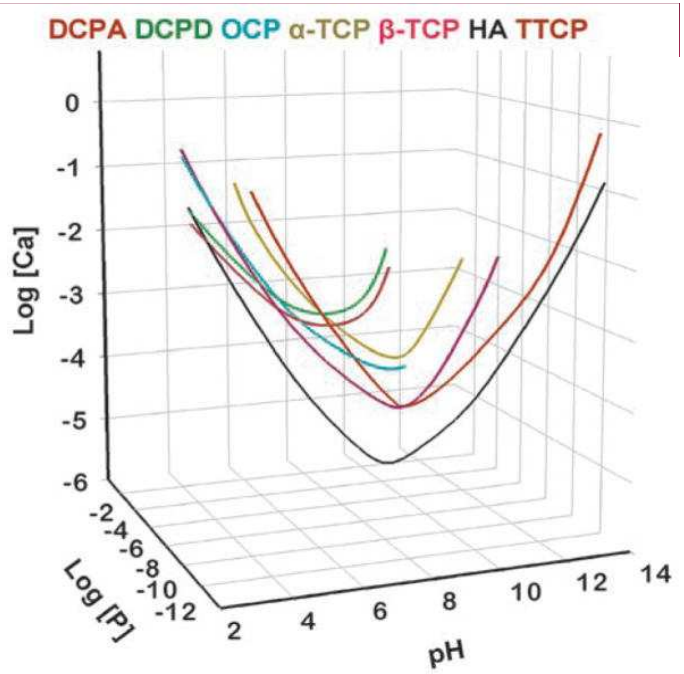
- “Bioactivity testing with SBF may lead not only to false positive but also to false negative results”

- “The use of an in vitro protocol for testing the bone bonding potential of a material remains a very attractive concept and should be contemplated very carefully”

4. Marc Bohner, Jacques Lemaitre Biomaterials 30 (2009) 2175–2179

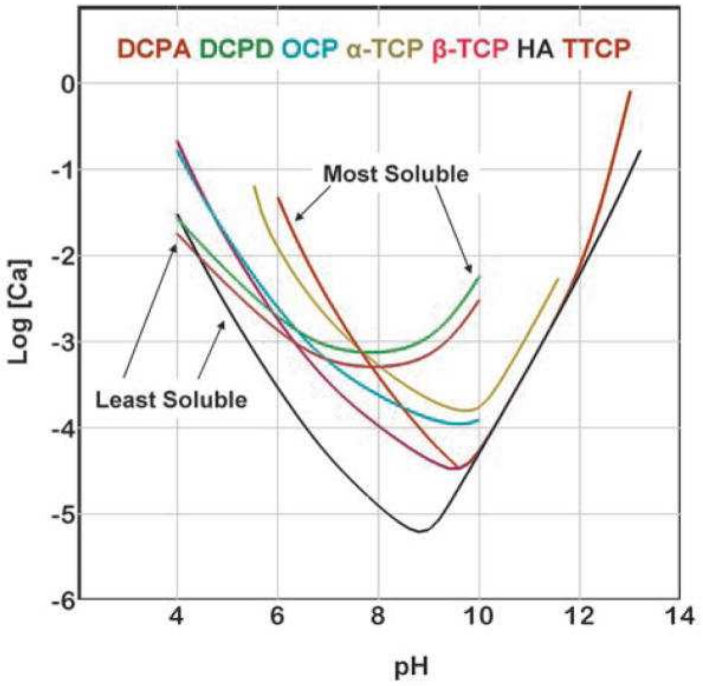
Ca P Salts Solubility

- For CaPs this can change with pH, conc. and temp.
- A salt whose isotherm lies below that of another is less soluble



At pH 7 the *in vivo* degradation rate of CaP can be predicted

MCPM > TTCP ≈ α-TCP > DCPD > DCPA > OCP > β-TCP > HA



CABER

Bioactive Bone Cements

Bone "Cement" differentiated from Bone "Substitute"

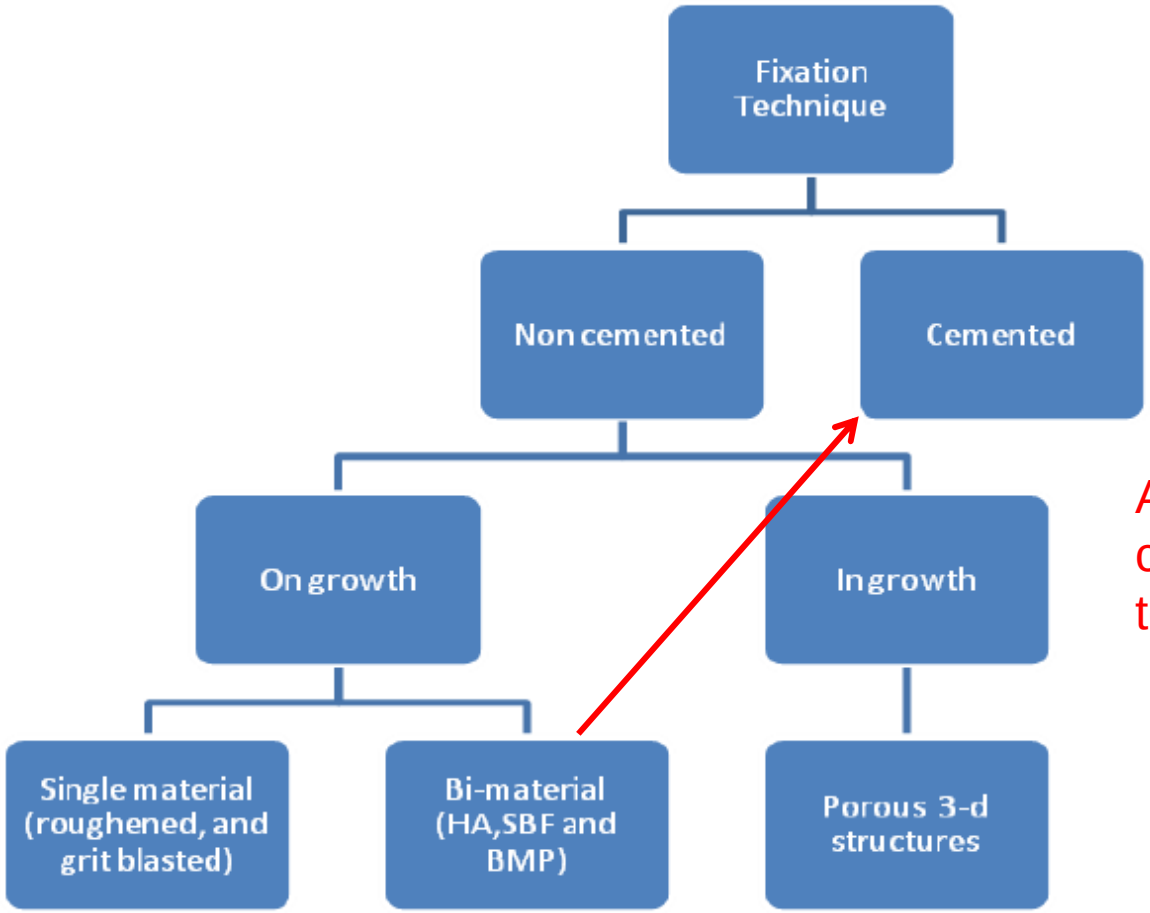
Implies:

- In situ setting – takes up form of individual defect
- Load bearing
- Adhesive (Necessary for stress transmission)
- Bioactive
- Fixation of other devices (Metal/Ceramic/Polymer)

Mutually Exclusive for high strength (density) ceramics

- **FDA Labelling : "Bone Void Filler intended only for orthopedic applications as a filler for gaps and voids that are not intrinsic to the stability of the bony structure"**

Fixation of Orthopaedic Devices



Add Bioactive components to cement

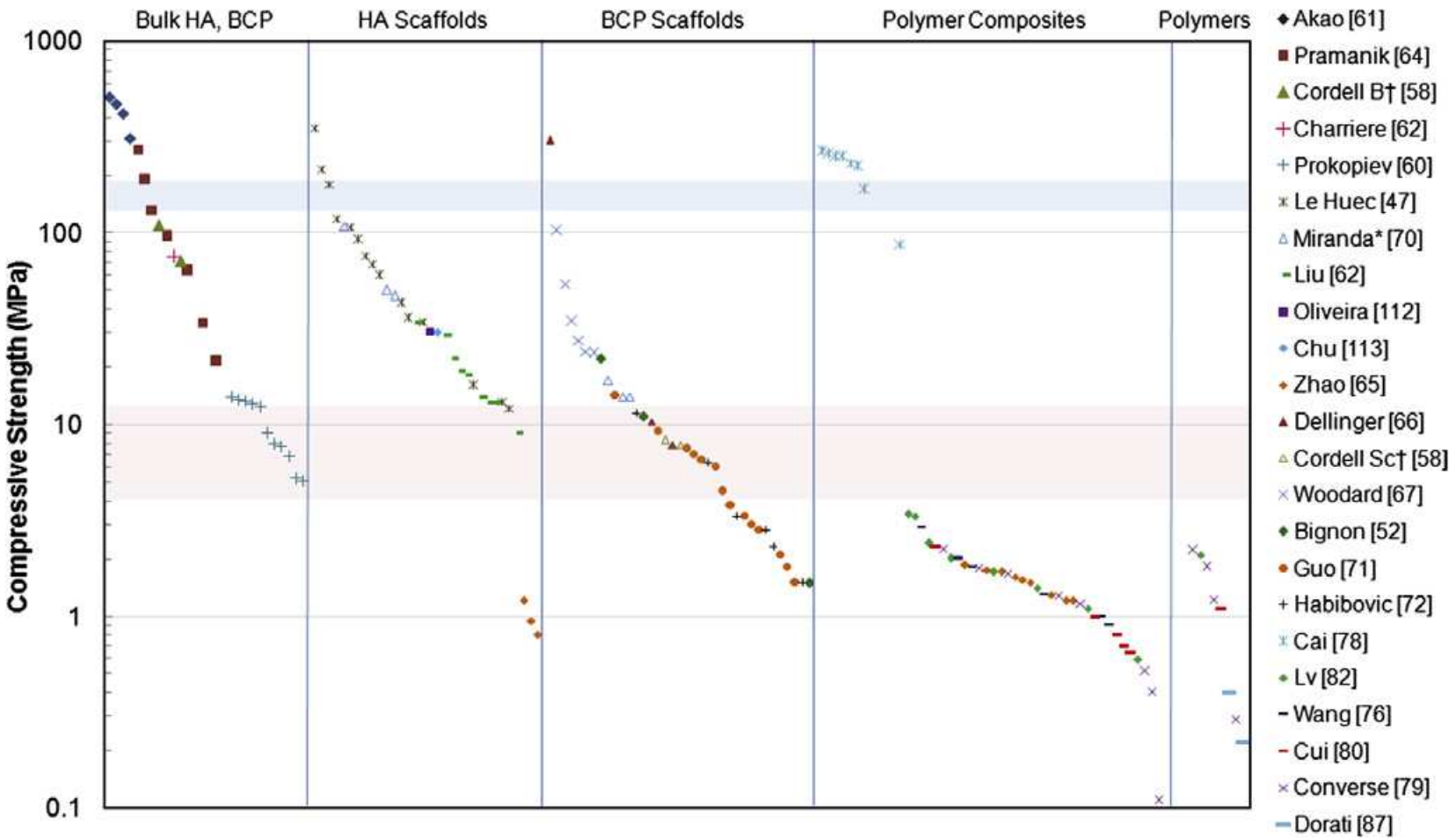
Design Criteria for Orthopaedic Bone Cement

- Ease of Placement and Handling
- Chemical Adhesion - Hydrophyllic
- Modulus Match with Bone
- Non-cytotoxic (no foreign body response)
- Bioactive (Osteoconductive / Osteoinductive)
- If resorption required – match regeneration rate
- Rapid Setting
- Dimensionally Stable
- Radiopaque
- Suitable Matrix for drug delivery
- Mechanical & Fracture Properties similar to bone at target site

Bone Cement Mechanical & Fracture Properties

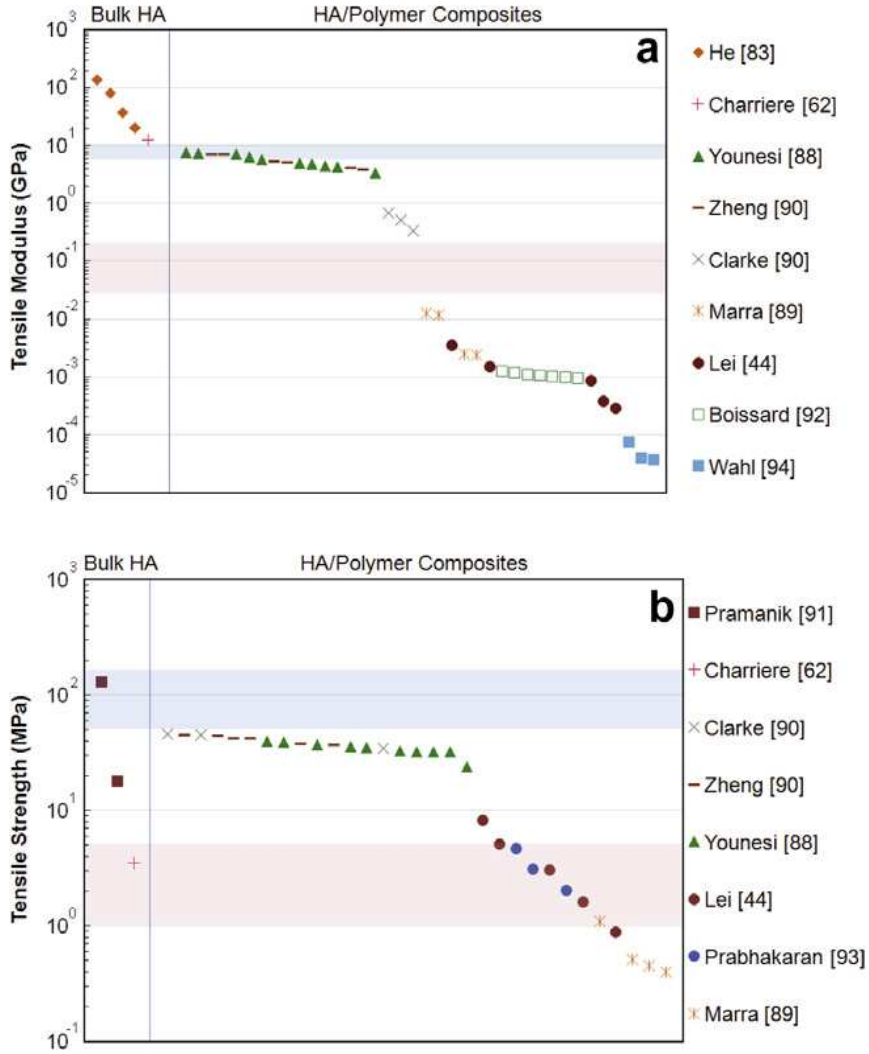
- Ceramic properties can be characterised as:
  - brittle (low fracture resistance, flaw tolerance)
  - low tensile strength (fibers are exception)
  - poor fatigue resistance (relates to flaw tolerance)
- Bone characterised as:
  - Composite in nature (>5 orders of magnitude in length scale)
  - Variable dependant on site and orientation
  - Viscoelastic
  - Poor fatigue resistance (but built-in repair mechanisms)
- Implies ideal bone cement should be composite (Biomimetic)

Compressive Strength of Bio-ceramics, Composites and Polymers [6]

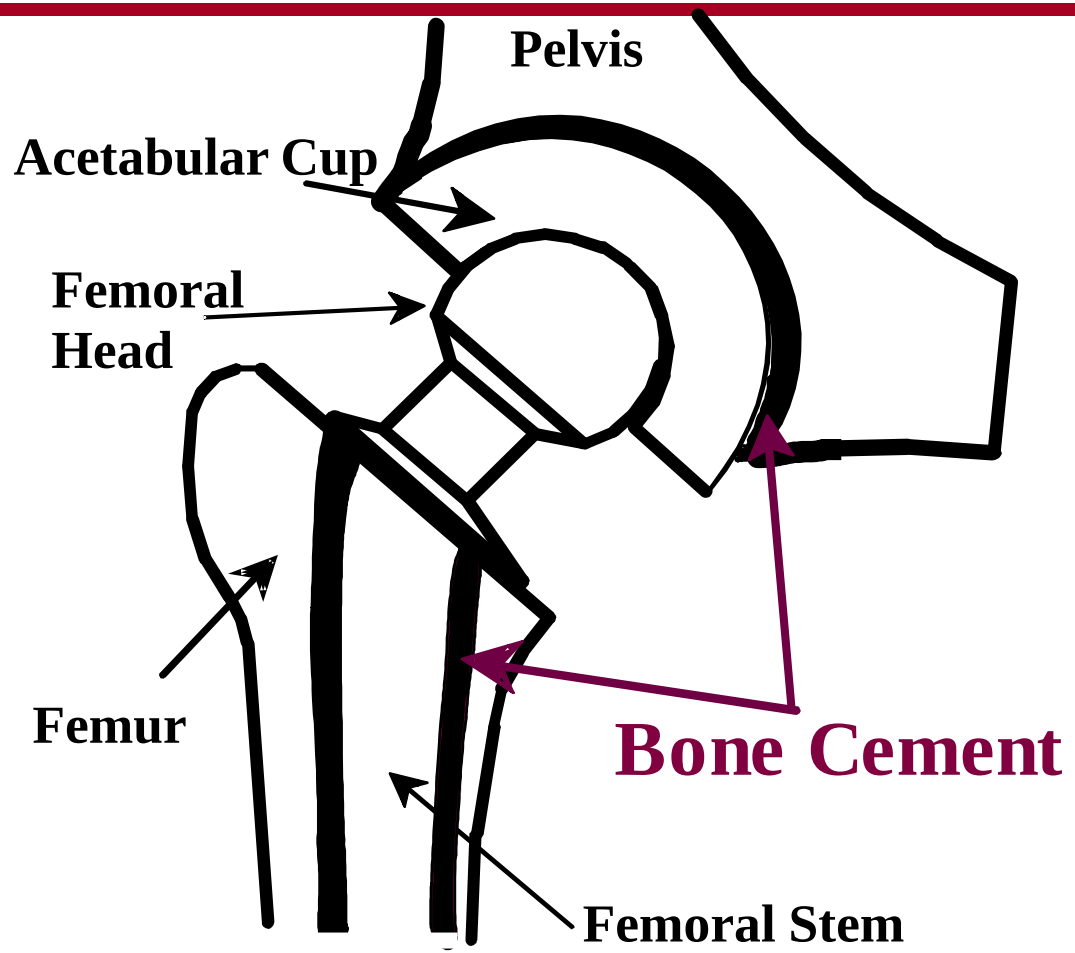


6. Amy J. Wagoner Johnson *, Brad A. Herschler Acta Biomaterialia 7 (2011) 16–30.

Tensile Modulus and Strength of Bio-ceramics, Composites and Polymers [6]



BONE CEMENTS



in TOTAL JOINT REPLACEMENTS

PMMA Bone cement

2-component system: powder and liquid mixed 2:1

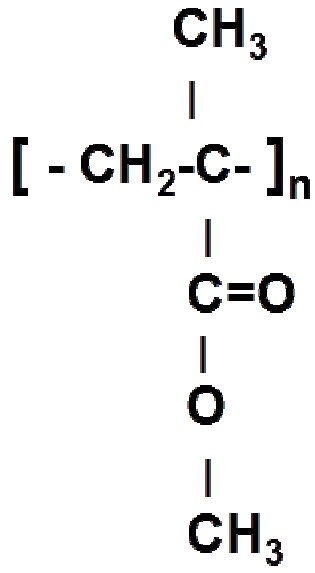
Powder

- PMMA/PMA/PS spheres 30-150um (>90%)
- Radiopacifiers ($BaSO_4$ /ZrO_2) (4-30%)
- Initiator (benzoyl peroxide) (2-3%)

Liquid

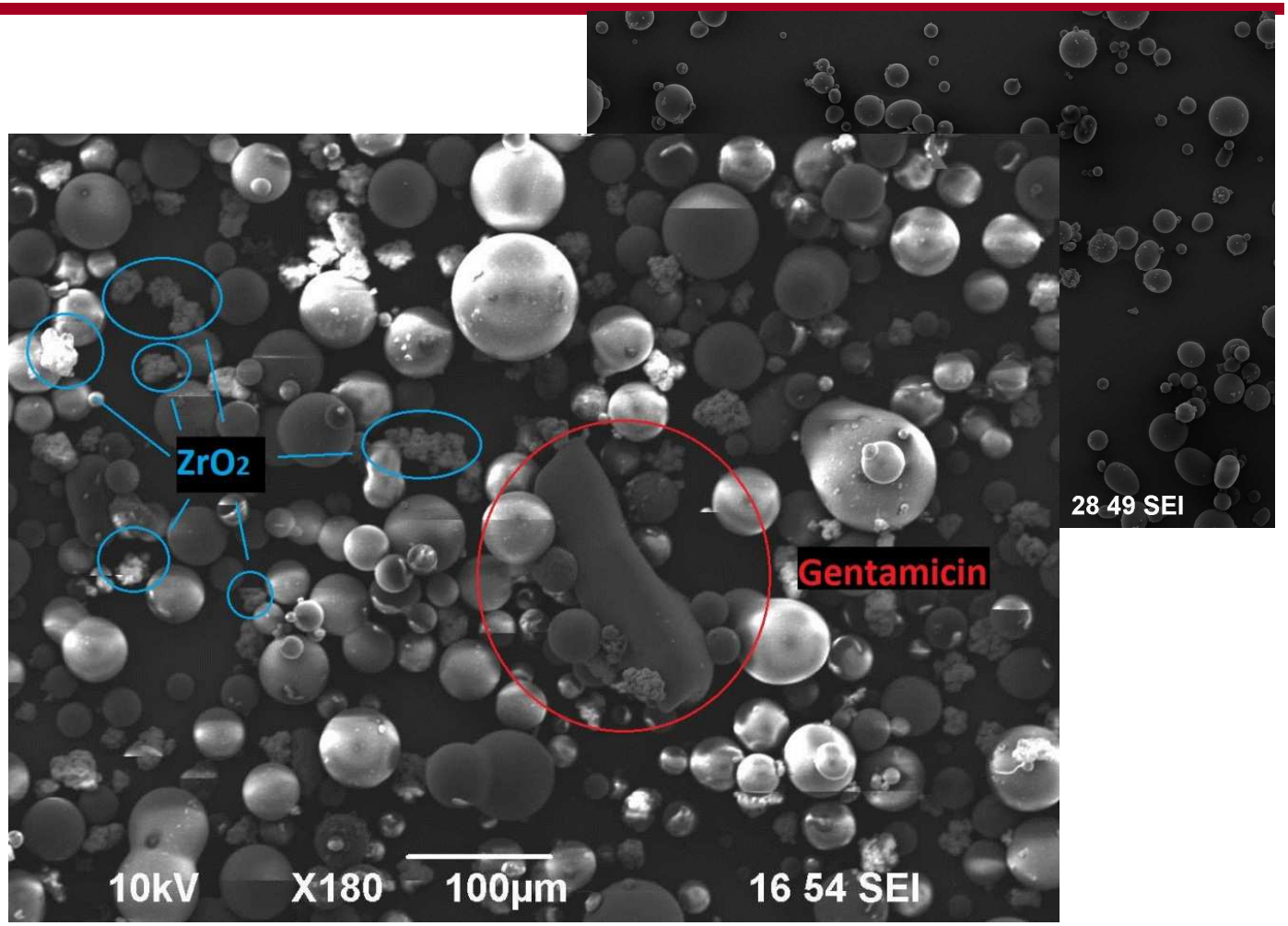
- MMA monomer (>85%)
- Co-monomers (10-15%)
- Inhibitor

Activator (Dimethyl-p –toluidine) (2-3%)



- Mix components together to a doughy stage
- Injected into prepared site, and allowed to cure via free radical polymerisation

Typical HV TKA Cement



PMMA Bone cement

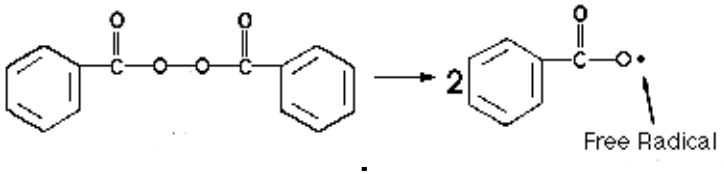
Free Radical Polymerisation:

Initiation → Propagation → Termination

Initiation:

The powder and liquid components have been mixed

The DMPT breaks down BPO to produce 2 free radicals:

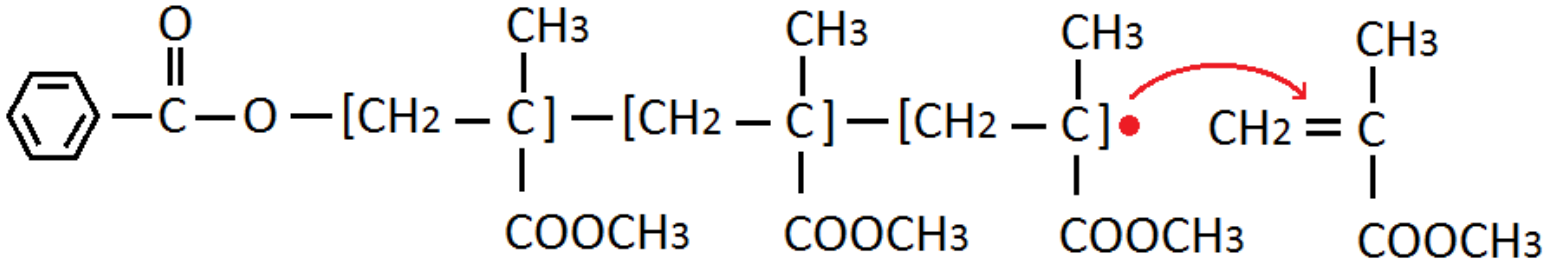


These free radica n at one end which denotes the active centre

This active centre is transferred to the end of the molecule as the polymer chain grows in size

PMMA Bone cement

Propagation:



Free radical attacks the C=C bond of the monomer, generating another radical

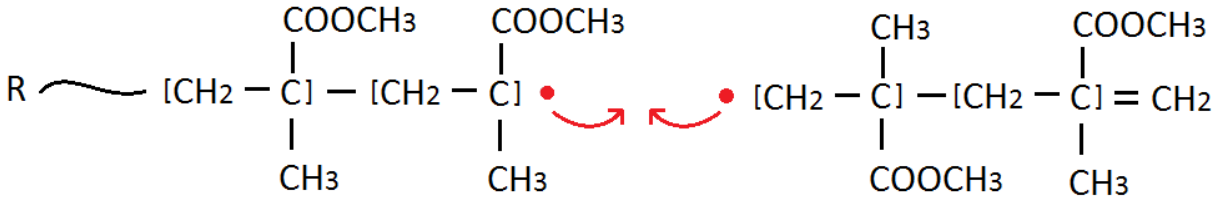
This radical attacks another molecule, adding to the growing polymer chain

This process continues growing the polymer chain until termination

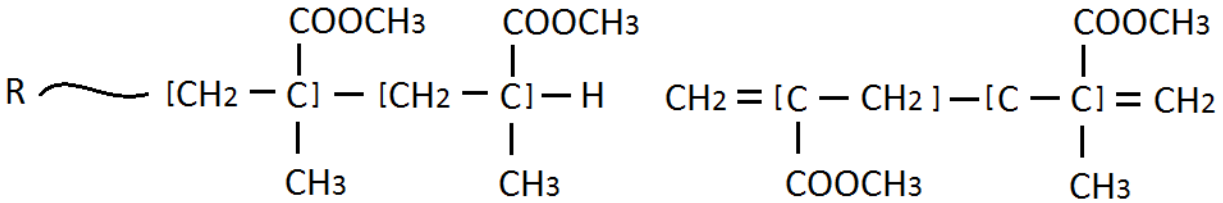
PMMA Bone cement

Termination:

- Combination:



- Disproportionation



PMMA Bone cement

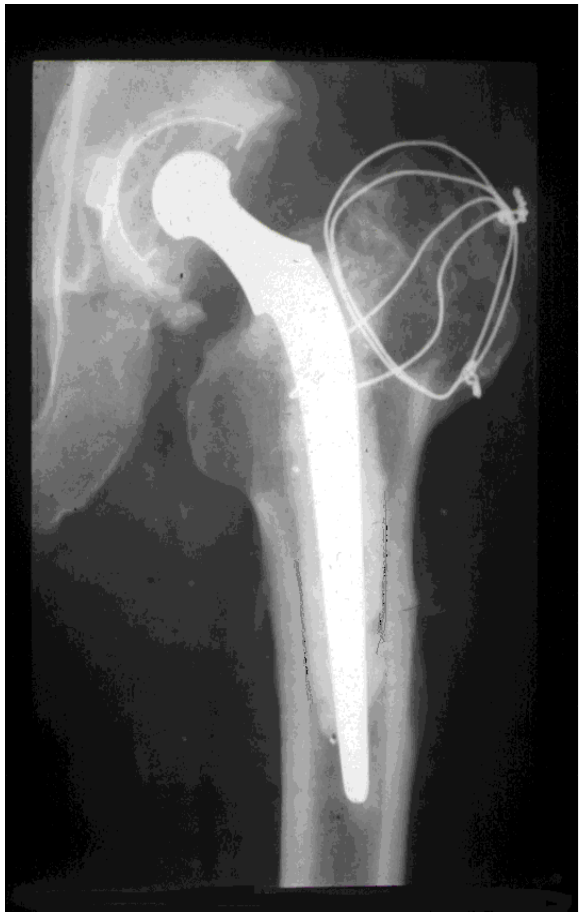
Trommsdorff effect:

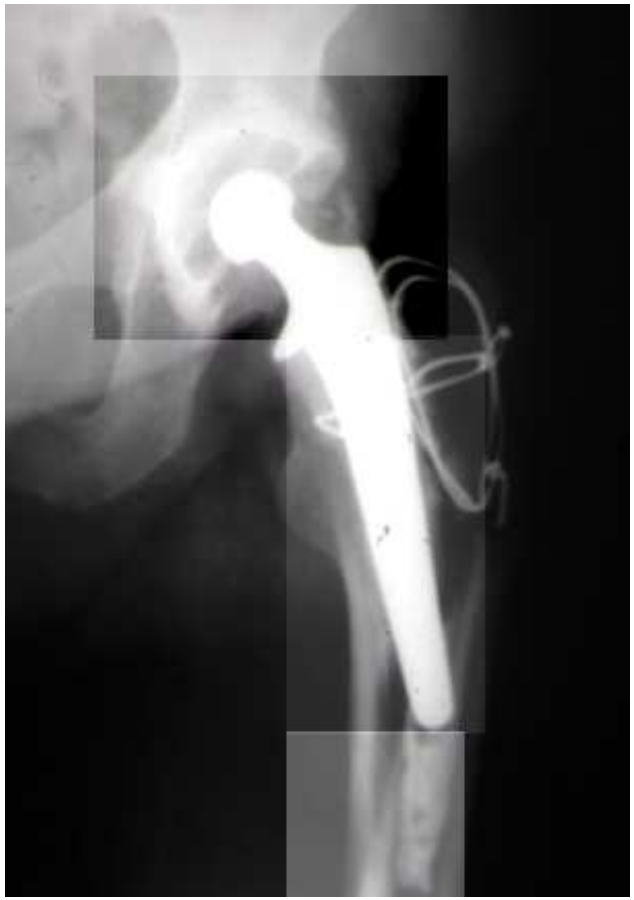
- An auto acceleration effect occurs at approximately 20-50% of conversion, due to an increase in viscosity
- In a more viscous medium, chain mobility is reduced, and the end chain radicals have a lower chance of being in a position to end termination
- However, small monomer molecules can still diffuse freely through the viscous medium to meet the active chain ends.
- As a result, there is a sharp increase in polymerization rate, which is accompanied by an increase in reaction exotherm
- This is why pre-polymer is added.

Causes for Revision (Mayo Clinic)

1. Aeseptic Loosening
2. Fracture
3. Dislocation
4. Infection

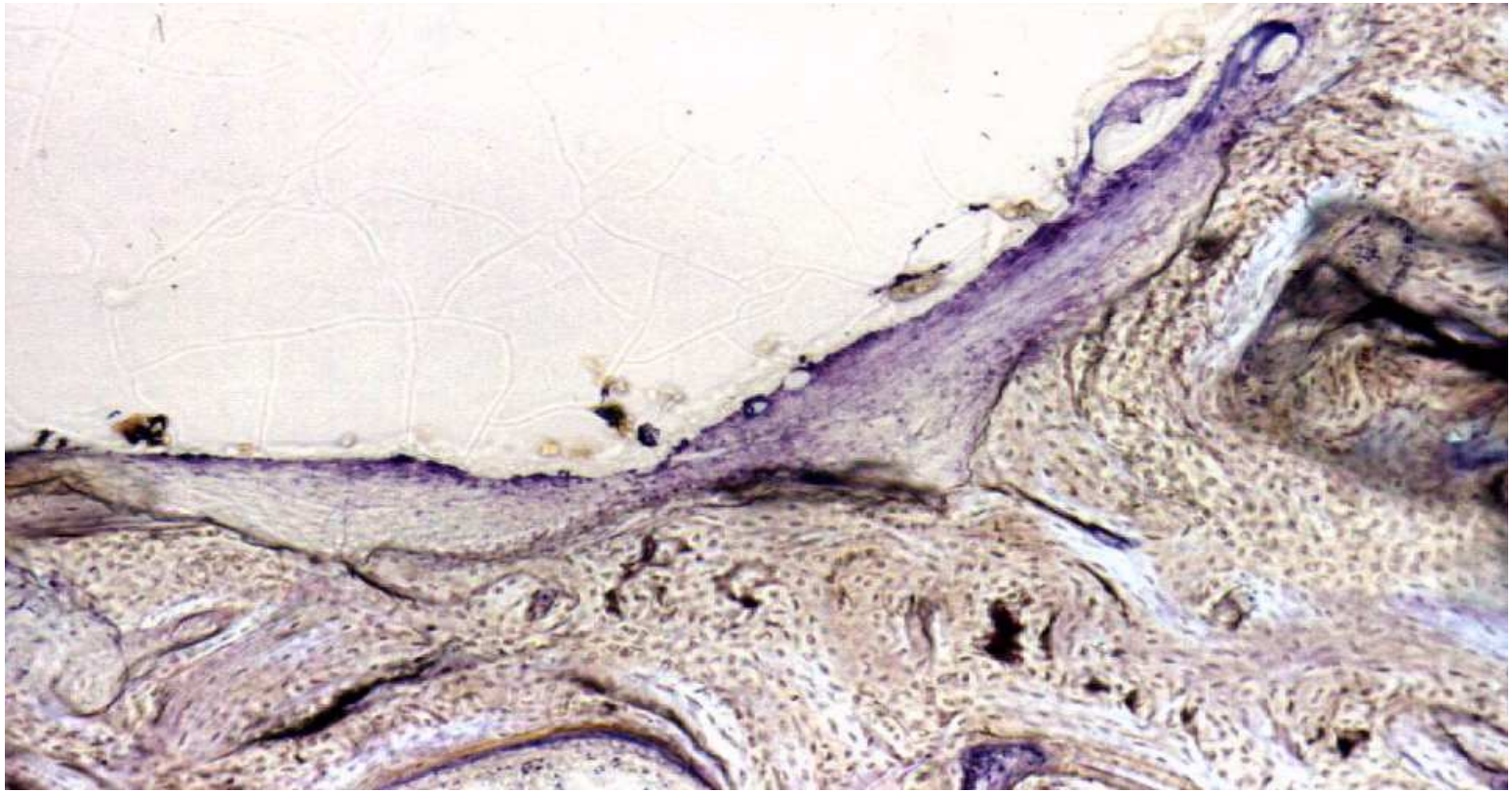
Aeseptic Loosening





Note the formation of a radiolucent layer as a result of fibrous capsule layer and stress shielding that leads to failure.

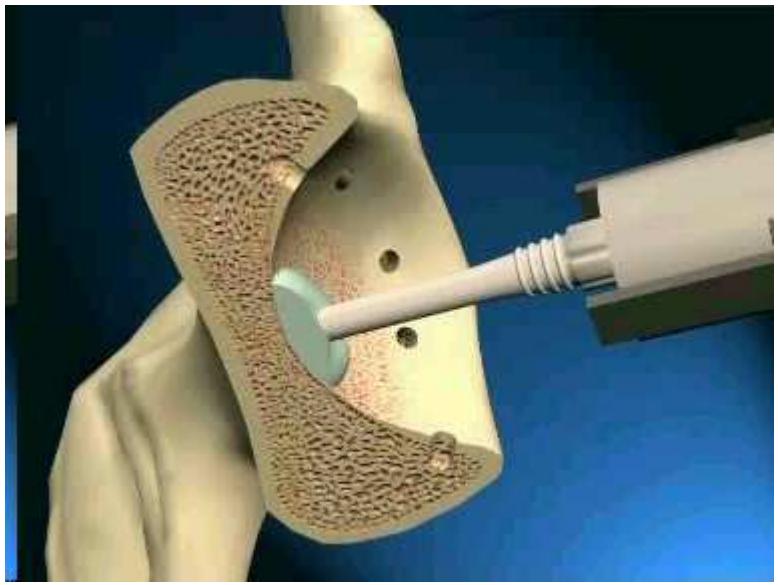
Fibrous Encapsulation



Fibrous reaction at the interface of PMMA and bone. A thickened, cellular, fibrous layer is present at the interface of the trabecular bone (Toluidine blue stained, ground section)

Contributions to Aseptic Loosening:

- Complex aetiology.
- No chemical bond.
- Thermal Necrosis.
- Chemical necrosis.
- Osteolysis

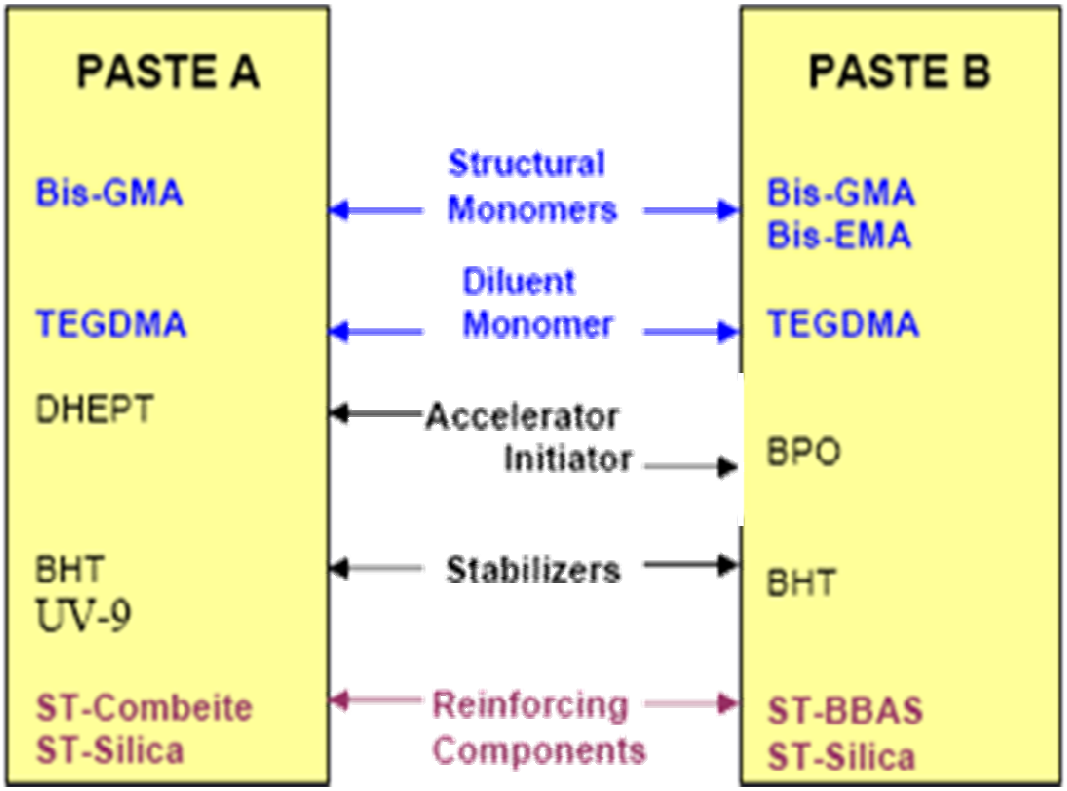


- Stress shielding –due to modulus mismatch.
- Shrinkage –up to 22%.
- Fibrous Capsule – Standard foreign body response

Properties Vs Design Criteria

Properties	PMMA bone cements
Quick setting (3 to 15 minutes)	Yes
Exotherm < 56° C	No
Matrix for drug delivery	No Intra operatively Yes
Osteointegrative (promotes bone growth)	No
Bioactive	if Bioactive ingredient added
Bioresorbable	No
Adequate viscosity	Yes
Radio-opaque	Yes if $BaSO_4$ or ZrO_2 is added
Modulus match with trabecular bone (~10-20 MPa)	No
Adhesive bond formation with bone/implant	No
Dimensional stability	No
• Fibrous encapsulation	
• Local toxicity monomer	
• Systemic toxicity –cardiovascular, liver & immune impairment	

“Bioactive” Resin Composite- Cortoss™



Bioactive Resin Composite- Cortoss™

Di-functional Monomers

- bisGMA
- bisEMA
- TEGDM

Reinforcing / Bioactive Fillers

- 45S5 Glass Ceramic (Combeite crystalline phase)
- Barium-Borosilicate glass

Activator + Initiator

- BPO
- DMPT

Bioactive Resin VCF Composite- Cortoss™

Di-functional Monomers

- Cross-linked Network – increased stiffness
- high degree of monomer conversion, lower exotherm-63^{0}C
- Higher Mw than MMA - decreased leachable toxic monomer

Reinforced with ceramic particles

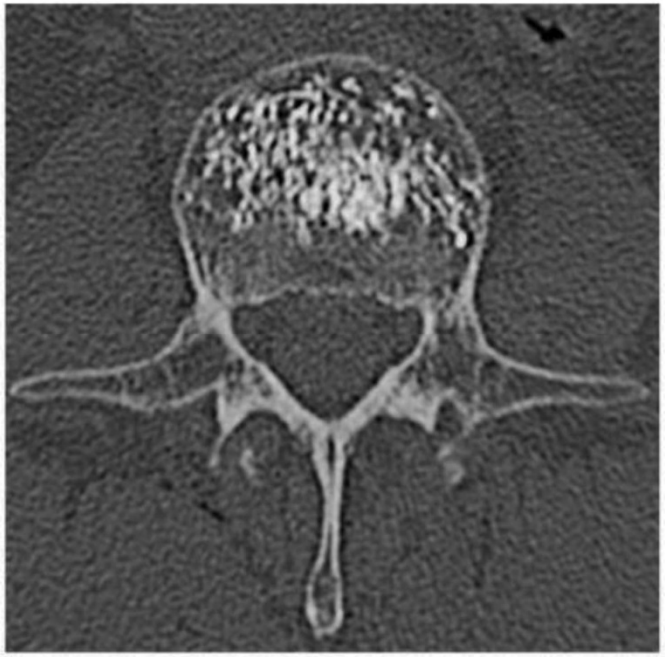
- increased stiffness

Bioactive Components

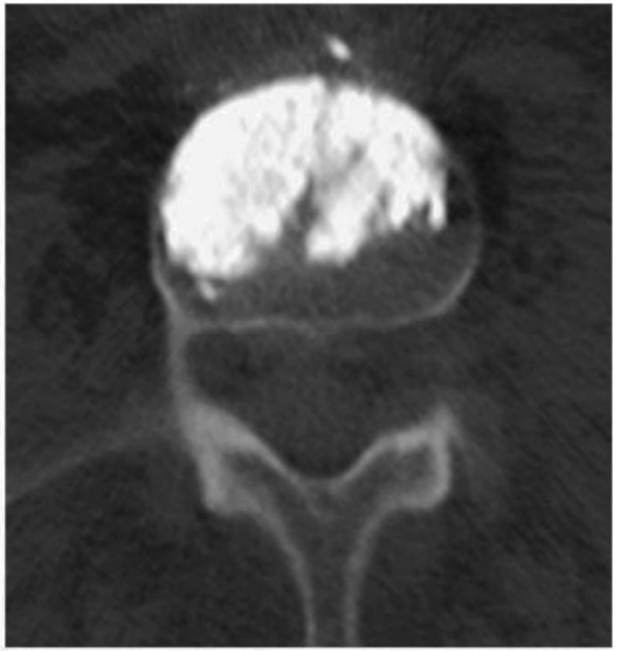
- Increased bone apposition at the interface
- Improved interfacial bond strengths between implant and bone

1. G.J. Pomrink, M.P. Dicicco, T.D. Clineff, E.M. Erbe, Biomaterials 24, 1023 (2003)
2. E.M. Erbe, T.D. Clineff, G. Gualtieri, Eur. Spine J. 10, S147 (2001)

Cortoss™ Dispersed Fill of Vertebral Body



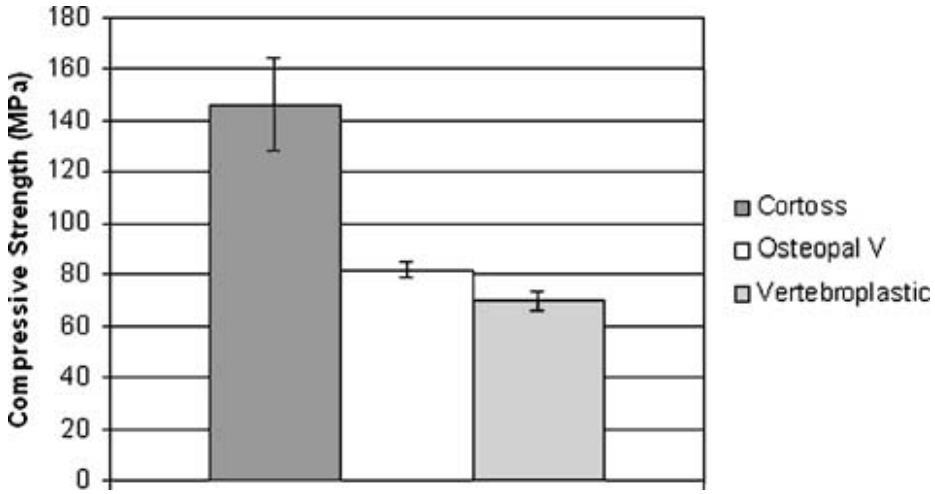
Cortoss

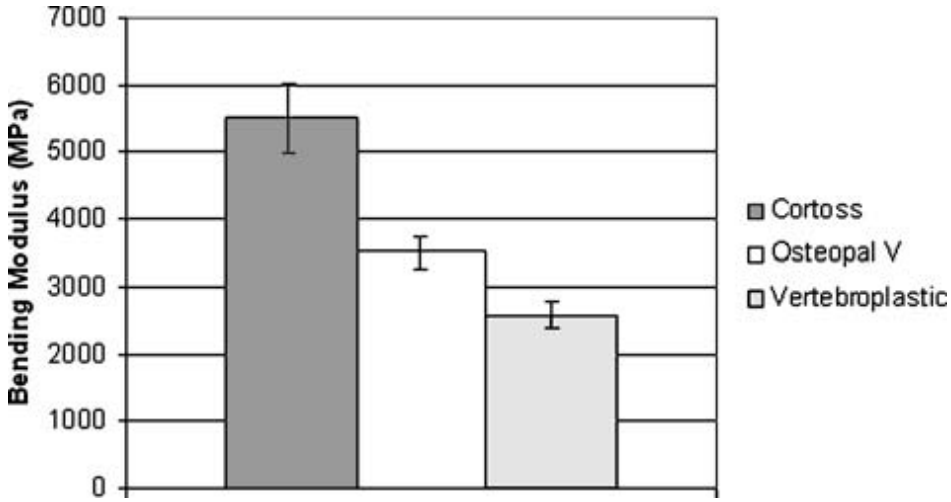


PMMA

1. **A Prospective Randomized FDA-IDE Trial Comparing Cortoss With PMMA for Vertebroplasty SPINE Volume 37, Number 7, pp 544–550 (2012)**

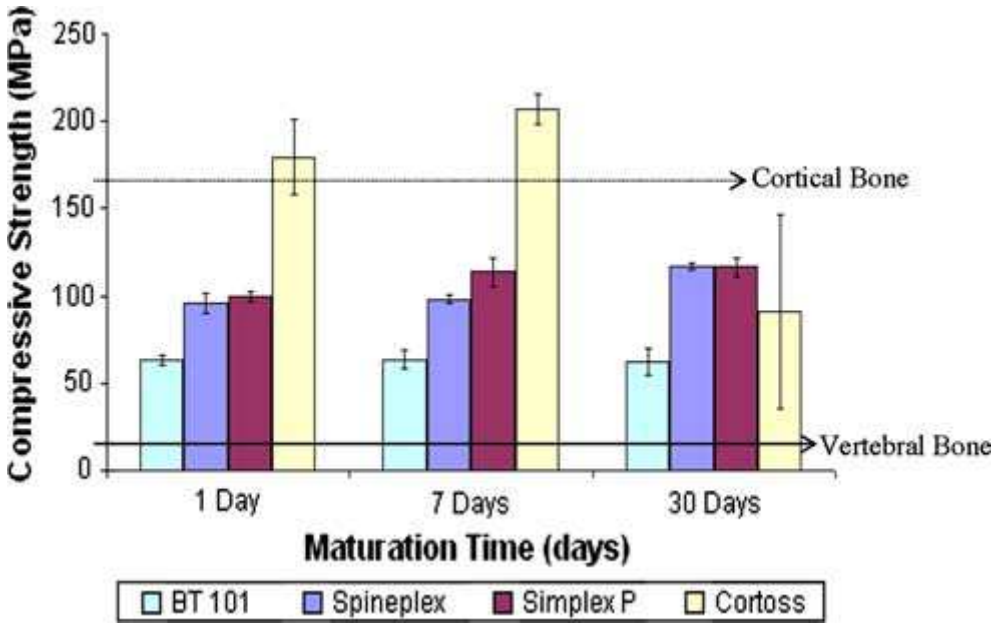
Cortoss™ Mechanical Property Comparison





1. **Sabina Gheduzzi · Jason J.C. Webb · Anthony W. Miles, J Mater Sci: Mater Med 17: 421–426 (2006)**

Cortoss™ Strength Loss with Time



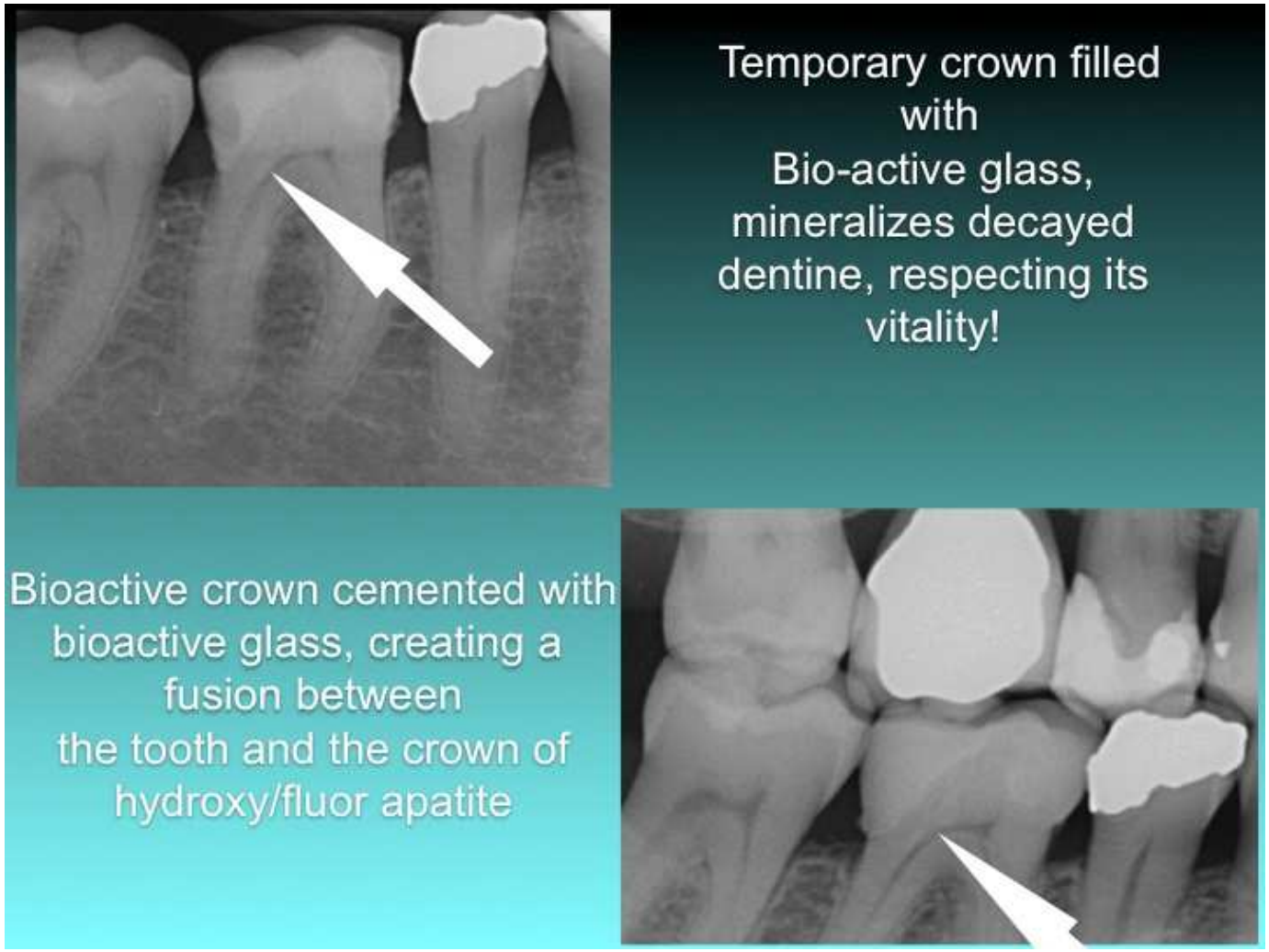
1. D. Boyd , M. R. Towler , A. Wren , O. M. Clarkin J Mater Sci: Mater Med 19:1745–1752(2008)

Bioactive Resin VCF Composite- Cortoss™

Disadvantages

- Exotherm- 63^{0}C
- Cold Chain Product
- bisEMA more prone to water uptake
  - Plasticisation of matrix – loss of stifness
  - Solubility of large Bioglass particles results in swelling and micro-cracking of matrix – loss of strength
- Bioactivity modest given majority of Bioglass is in crystallised form
- Brittle K_{IC} ~ 0.7 MPa$\sqrt{m}$


Cavity under
amalgam restoration
After crown preparation
more caries developed


Temporary crown filled with
Bio-active glass, mineralizes decayed dentine, respecting its vitality!
Bioactive crown cemented with bioactive glass, creating a fusion between the tooth and the crown of hydroxy/fluor apatite

Can a BisGMA Composite be made REALLY Bioactive?

- Yes
- Incorporate BAG of greater bioactivity than 45S5…

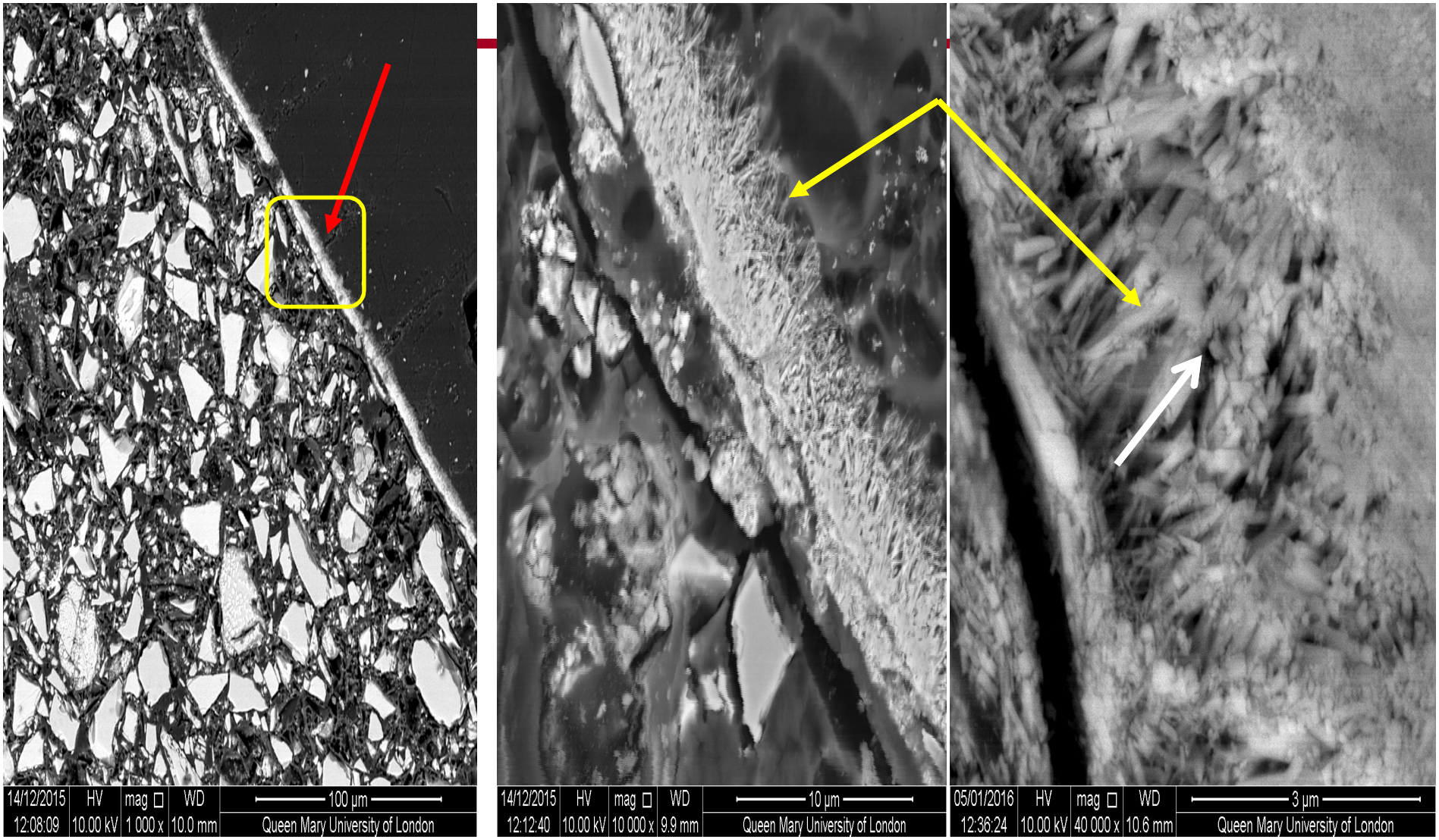
BAG Filed BisGMA Composite QMUL 2016

Verify via

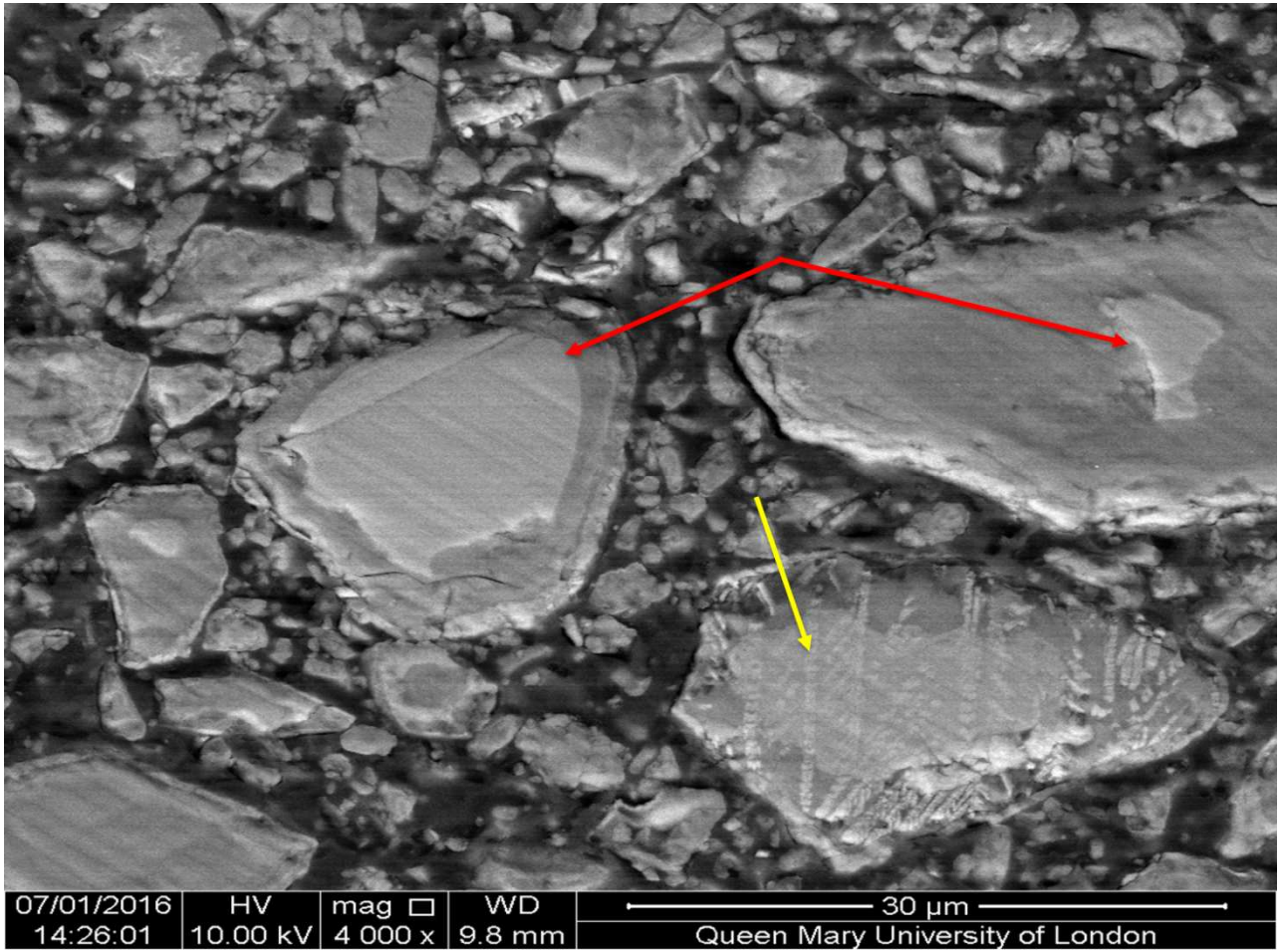
- Age in
  - SBF / Artificial Saliva / TRIS Buffer
    - Static – Assess Ca P Deposition (volumetric)
    - Dynamic – Assess Solution Concentration (Flux)in sink conditions

    NB Ionic Strength
- FTIR
- XRD
- MAS NMR

BAG Filed BisGMA Composite QMUL 2016



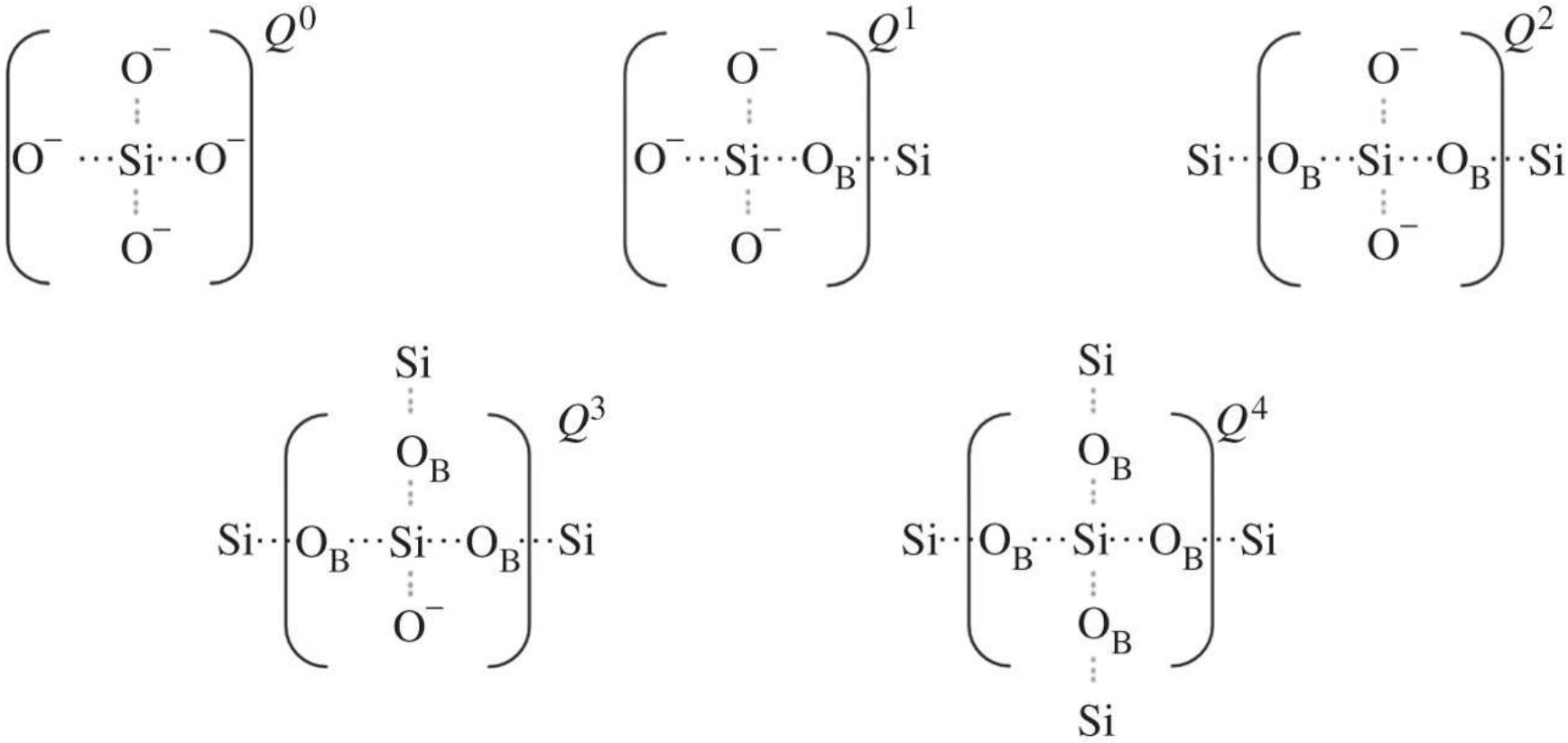
BAG Filed BisGMA Composite QMUL 2016



Glass Structure

- **Glasses comprise:**
- Network Formers. Form the 3D backbone of the glass. Eg SiO_2.
- Network Modifying Oxides. Break up the glass network eg Na_2O, K_2O, CaO, SrO.
- Bridging Oxygens (Si-O-Si).
- Non-Bridging Oxygens $Si\text{-}O^-\ Na^+$.

Schematic of the different Q structures that can describe Si network connectivity in glasses.



O_B represents a network-forming bridging oxygen

Network Connectivity

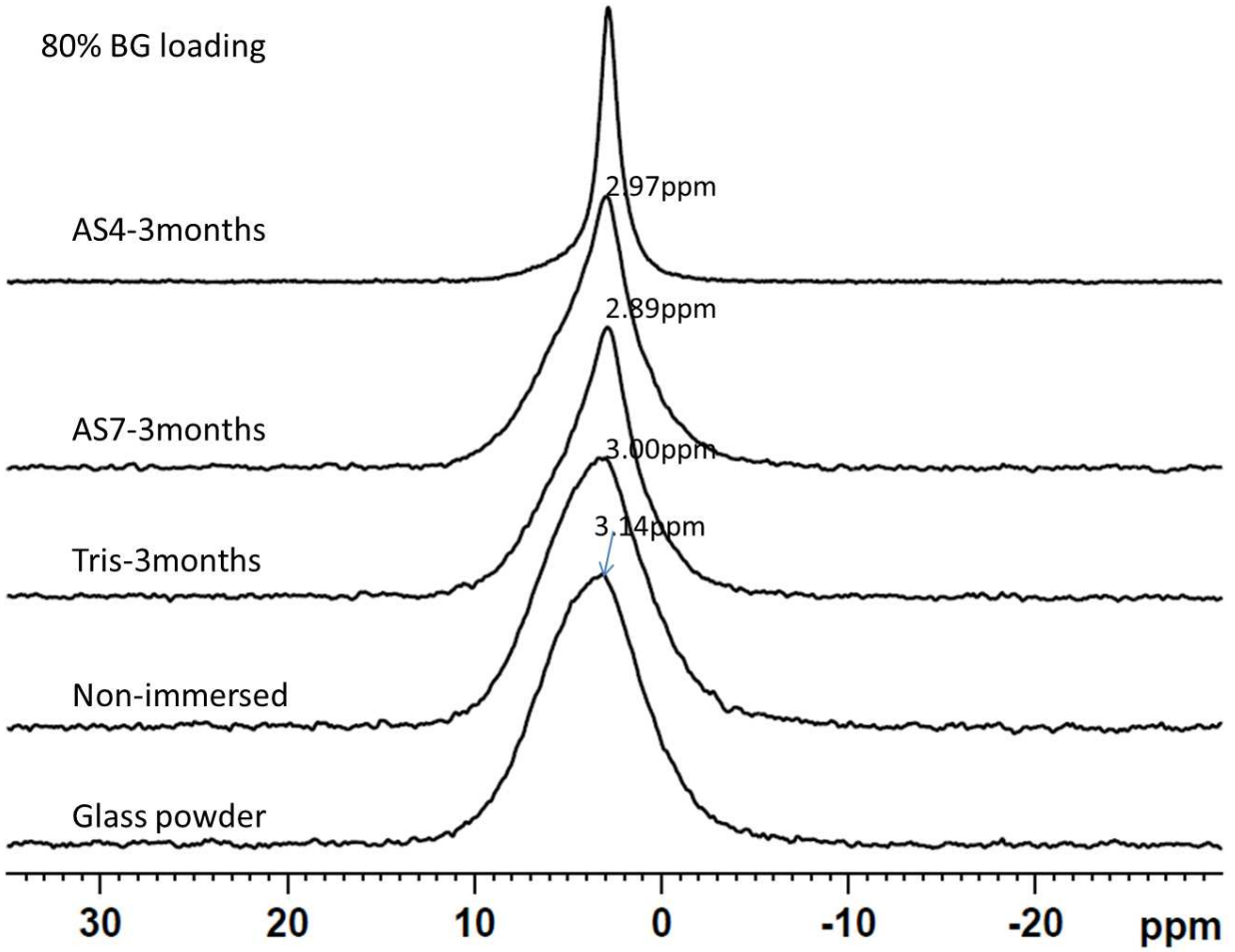
$$NC = 2 + \frac{[(2 \times SiO_2) + (2 \times P_2O_5)] - [2(M_2^IO + M^{II}O)]}{SiO_2 + (2 \times P_2O_5)}$$

The formula above assumes that P atoms are in network forming role in a range of Q^n structures, and the version below assumes that P is an orthophosphate Q^0 structure and requires modifier cations in a charge balancing role

$$NC = \frac{4[SiO_2] - 2[M_2^IO + M^{II}O] + 6[P_2O_5]}{[SiO_2]}$$

where M_2^IO and $M_2^{II}O$ are the mono- and divalent modifier oxides in the glass

BAG Filled BisGMA Composite ^{31}P MAS NMR

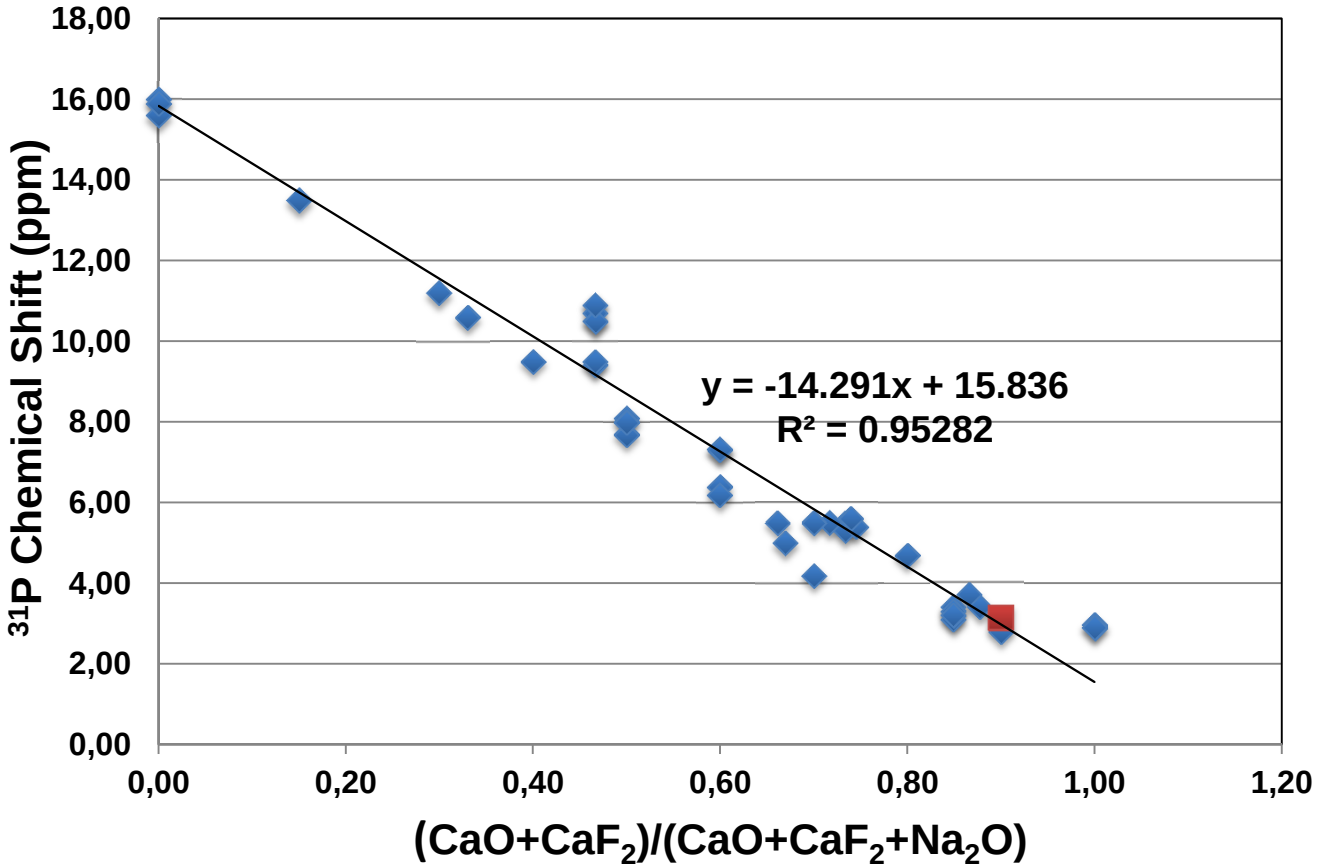


^{31}P chemical shift, ppm

BAG Filed BisGMA Composite QMUL 2016

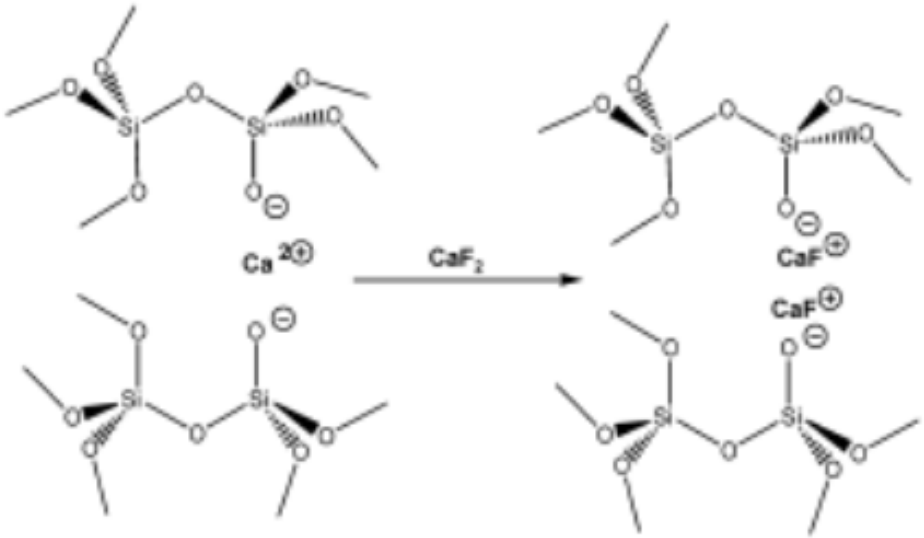
- The ^{31}P MAS-NMR spectra of the glass and the non immersed composite exhibit a broad peak at approximately 3ppm corresponding to a mixed Q^0 orthophosphate PO_4^{3-} species charge balanced by Ca and a small amount of Na.
- With increasing immersion time a sharp peak at 2.8-2.9ppm develops corresponding to apatite and increases with time with the broad signal from the original glass simultaneously disappearing.
- By 3 Months there 31P MAS-NMR signal corresponds to only apatite indicating that **all** the phosphorous content of the glass has been consumed and has been **converted to apatite** within the composite disc. Bulk (as opposed to surface) assessment of reactivity
- The charge balancing of the orthophosphate would be expected to correlate with the $CaO/(CaO+Na_2O)$ ratio of the glass composition

Predicted ^{31}P MAS NMR Chemical Shift

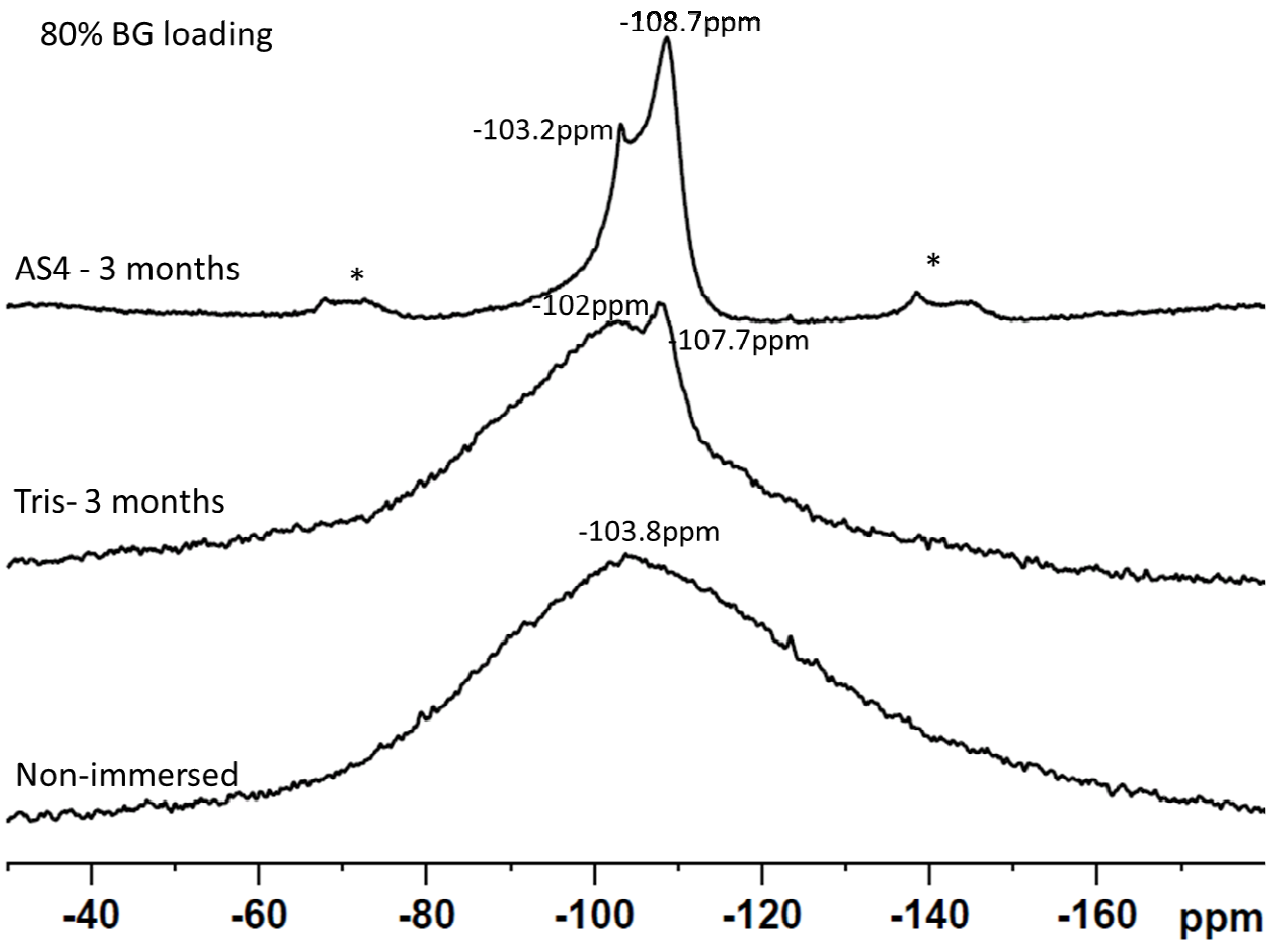


Example Ionomer Glass -Sodium Series

Peak	Species	Chemical shift, ppm	Percentage
1	F-Ca(n)	-97.7	**44.9**
2	F-Ca(3)Na(1)	-130.2	**7.6**
3	Al-F-Ca(n)	-158.3	**37.8**
4	**Al-F-Na(n)**	**-189.0**	**9.6**



BAG Filled BisGMA Composite ^{19}F MAS NMR



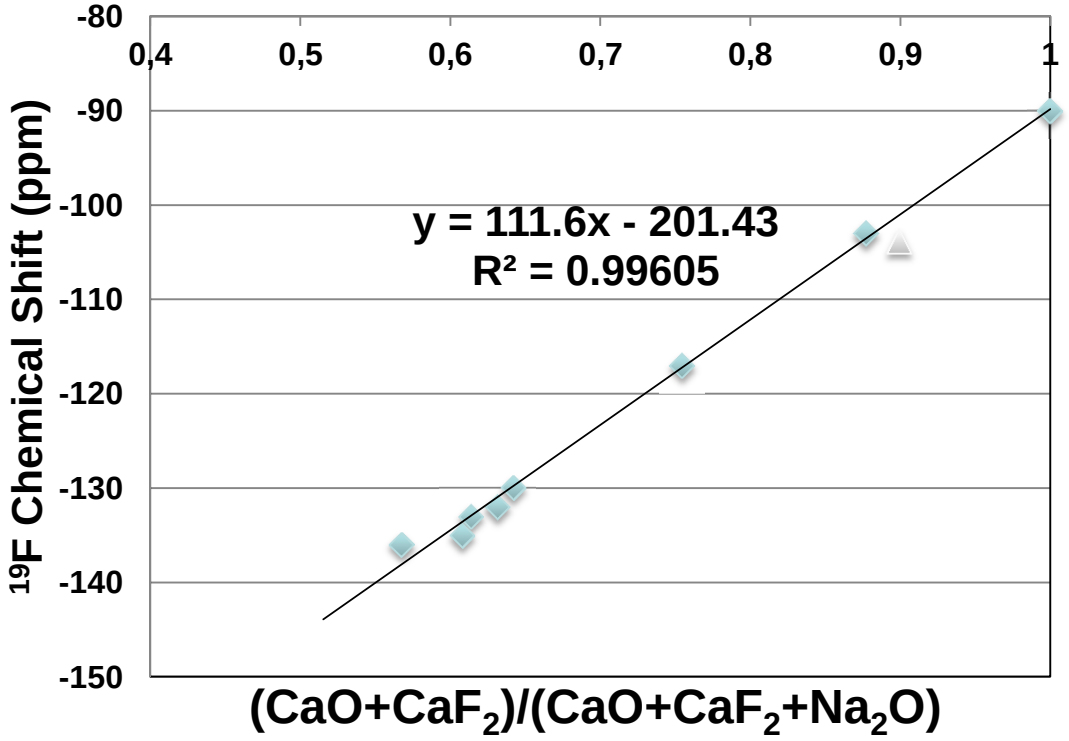
^{19}F chemical shift, ppm

BAG Filed BisGMA Composite QMUL 2016

- F was complexed by Ca in a sodium free and the
- dominant species present F-Ca(n).
- Given the low Na_2O content of the glasses the dominant species are likely to be F-Ca(n) species where n is 3/4.
- The ^{19}F Chemical shift for an F-Ca(n) species is about -100ppm and the peak exhibited a maximum at a chemical shift of -103ppm.
- With increasing immersion time the broad peak from the original glass disappears and two new sharper peaks at -103 and -108ppm develop corresponding to fluorapatite(FAP) and calcium fluoride (CaF2). There is probably a third peak present at -105ppm corresponding to possibly a mixed fluorohydroxyapatite. By 3 Months the broad signal from the original glass has been lost indicating that all the original fluorine in the glass has been consumed in forming largely FAP and CaF2.
- The formation of CaF2 is considered undesirable and indicates the fluoride content of the glass is too high to be ideal.

^{19}F Chemical Shift for Glass

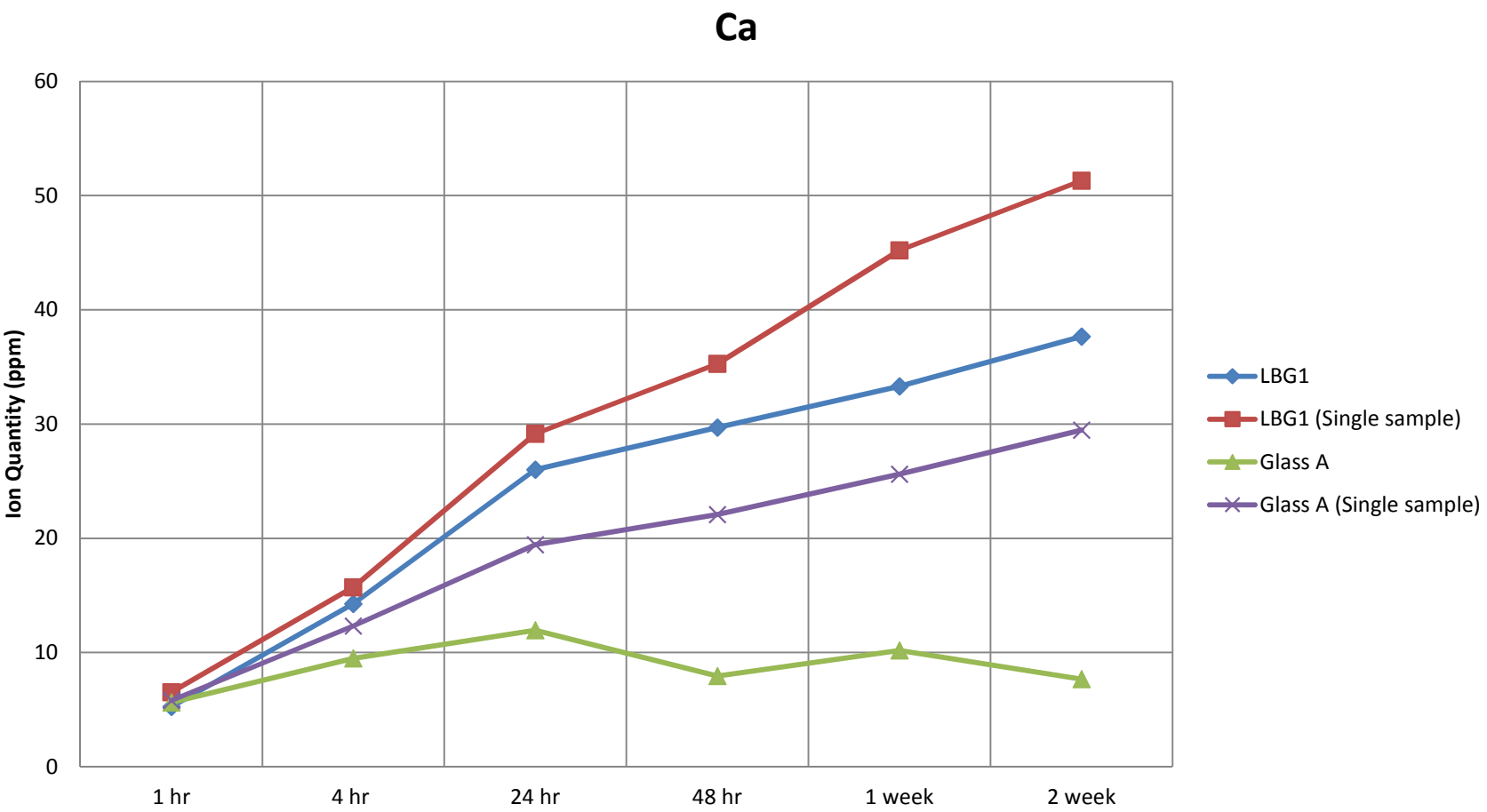
- Prediction based on Ca/Na ratio -100ppm.
- Based on ^{31}P chemical Shift -87ppm.



^{19}F chemical shift, ppm

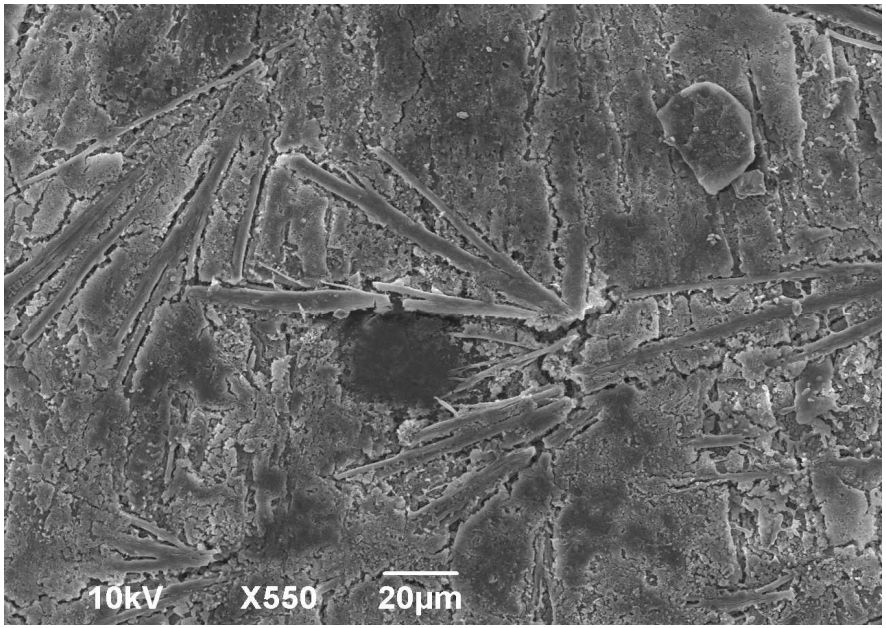
PMMA Bone Cement be made REALLY Bioactive?

Conventional PMMA Cement + BAG

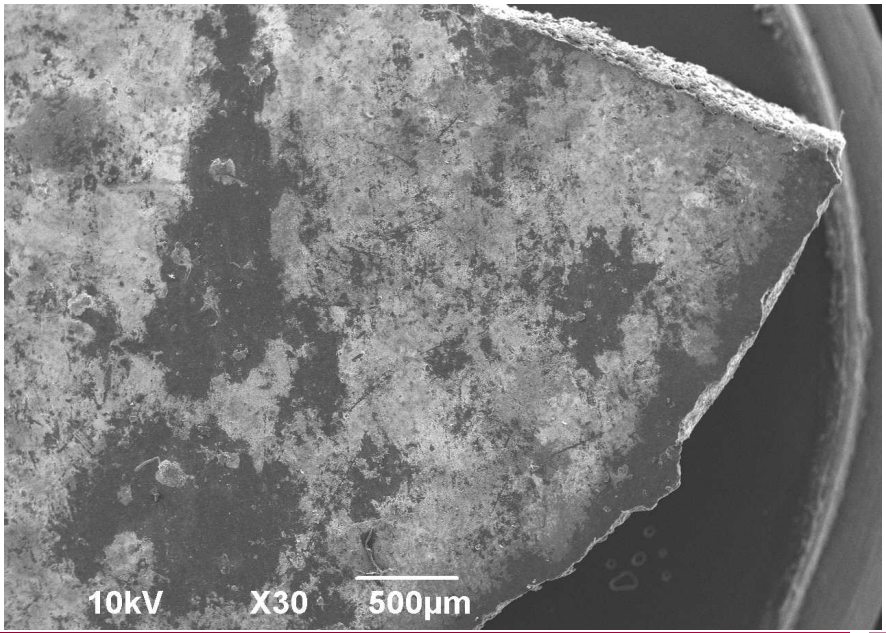


TRIS Buffer Dynamic @37 C

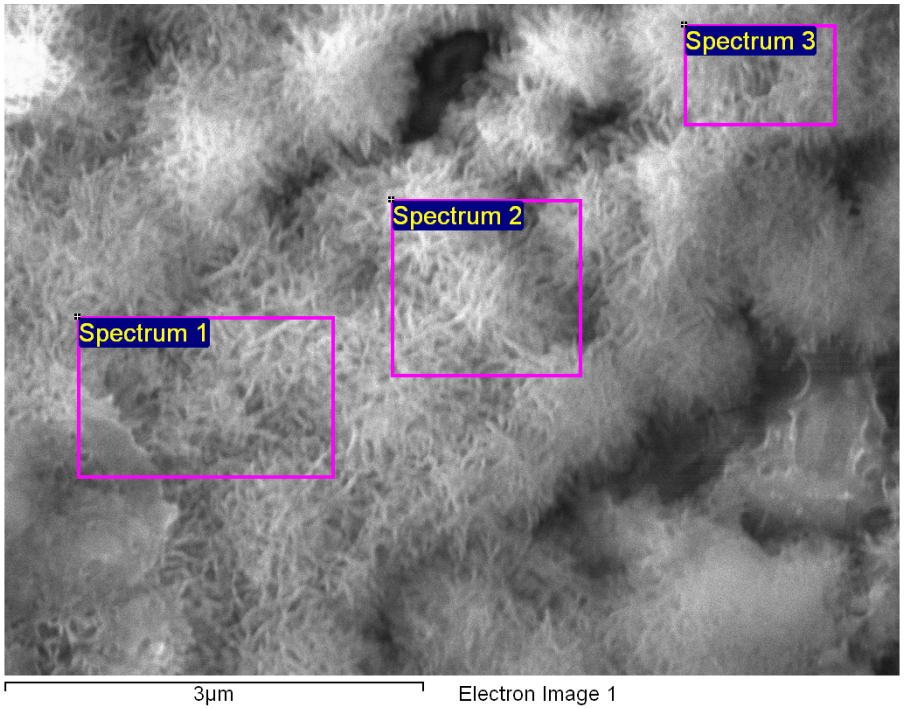
Conventional PMMA Cement + BAG



TRIS Buffer 6 Hours Static



Conventional PMMA Cement + BAG



TRIS Buffer 6 Hours Static

Spectrum	In stats.	Na	Si	P	Ca	Total	
Spectrum 1	Yes	7.28	2.78	29.82	60.12	100.00	
Spectrum 2	Yes	8.65	7.20	28.62	55.53	100.00	
Spectrum 3	Yes	8.90	13.37	27.12	50.61	100.00	
Mean		8.28	7.78	28.52	55.42	100.00	
Std. deviation		0.87	5.32	1.35	4.75		
Max.		8.90	13.37	29.82	60.12		
Min.		7.28	2.78	27.12	50.61		

Predicting the bioactivity of glasses using the network connectivity or split network models

Conclusion:

The network polymerisation (Q^n structure) strongly influences glass dissolution and subsequent apatite formation, and the NC or split network models are useful and successful in predicting bioactivity

i) They do not take account of the nature of the network modifying cations, in particular their charge to size ratio and their influence on the glass network.
ii) They equate glass dissolution directly to bioactivity.

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Predicting the “bioactivity” of Cements

Conclusion:

Can a cement be too bioactive?

Yes – in vivo mineralisation of :

- Adjacent soft tissue (!)
- Adjacent neural tissue (!!!!)

Network Connectivity Models can predict dissolution

Which in turn

Can be used to design materials exhibiting varying flux of ions which should be assessed for actual biactivity IN VIVO

Robert G. Hill, Delia S. Brauer Journal of Non-Crystalline Solids 357 (2011) 3884–3887

Predicting the “bioactivity” of Cements

Conclusion:

Network Connectivity Models can predict dissolution

Structural role of modifier and intermediate cations depends on type, ratio and quantity of other cations

Bioactivity assessment best done via total quantity or total flux of ions in entire system, informed by chemical equilibrium of that system

Bioactivity not generalised characteristic – should be tailored for specific indication of anatomical site and defect size

Robert G. Hill, Delia S. Brauer Journal of Non-Crystalline Solids 357 (2011) 3884–3887

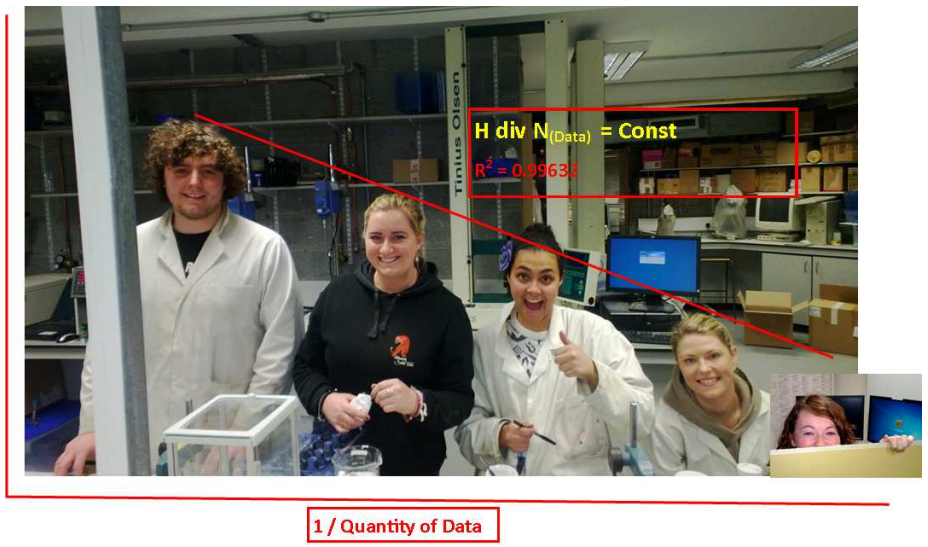
Acknowledgements

Dr Ian Houlihan UL

Dr Mai Huang QMUL

SS- MAS NMR

- Prof Robert Hill QMUL
- Dr. Natalia Karpukhina QMUL
- Dr Rob V. Law Imperial



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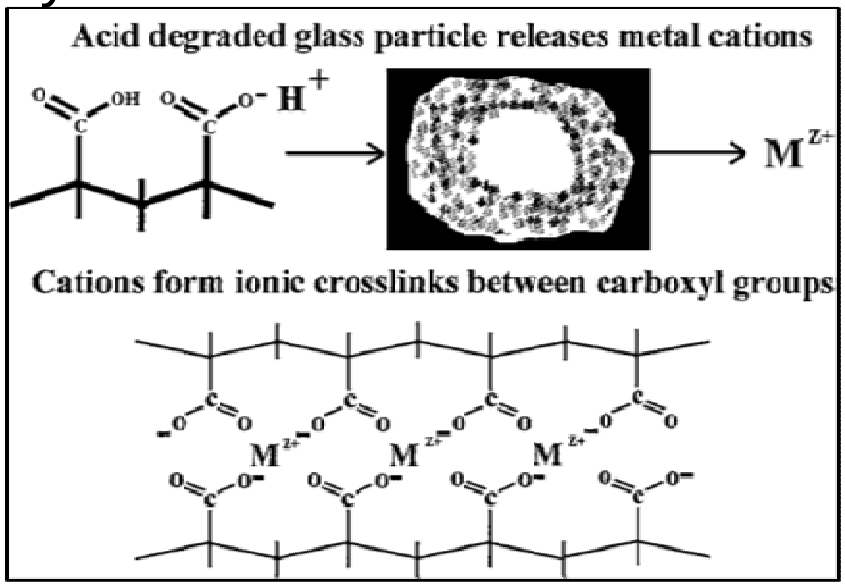
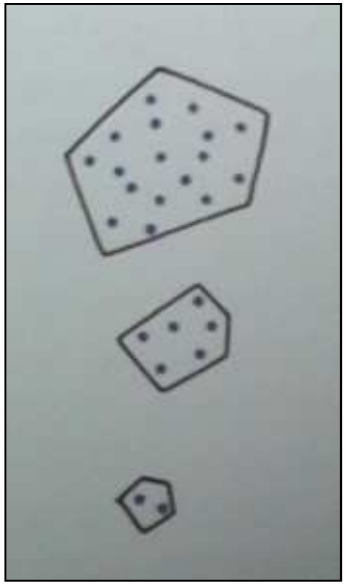
Glass Ionomer Cements

- Bioactive cement system
- Ion leachable glass powder, poly (acrylic) acid and water
- Carboxylic acid hydrolyses and degrades the glass, releasing ions
- Ions are chelated with COO^- groups
- Crosslinking of the polyacrylate chains, embedding glass particles in polysalt matrix



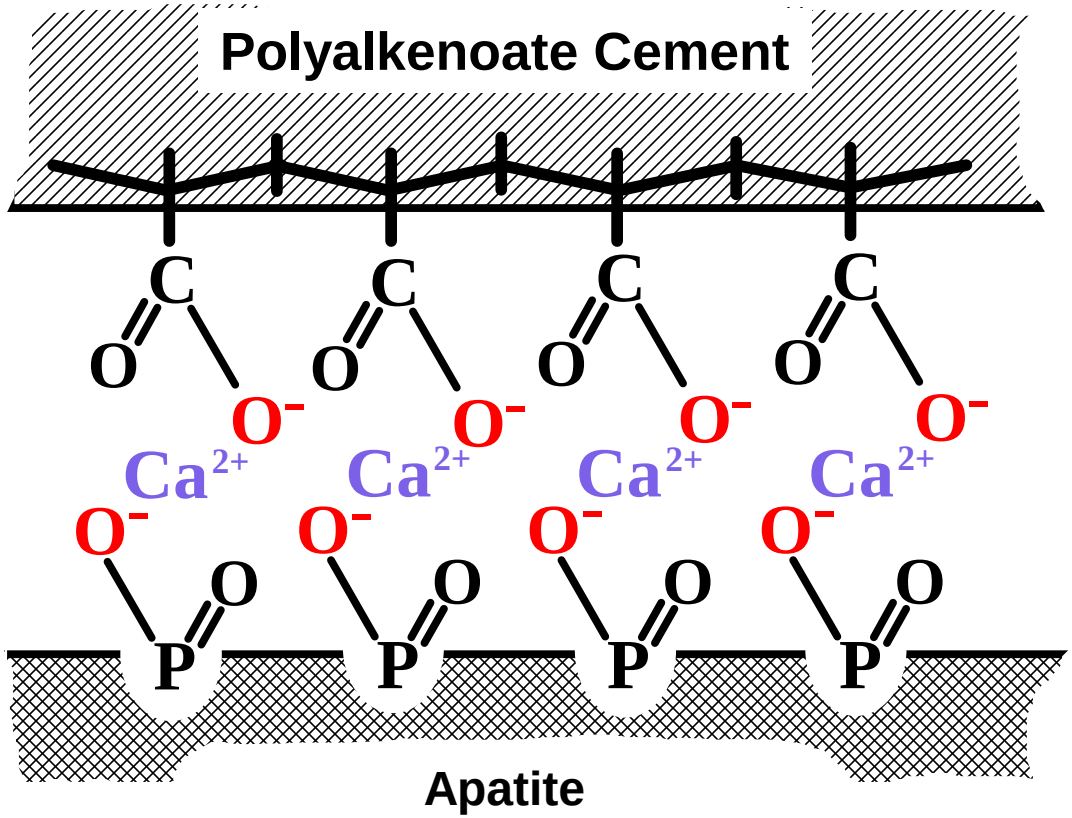


4. De Barra, E. & Hill, R. 1998. Influence of poly(acrylic acid) content on the fracture behaviour of glass polyalkenoate cements. *Journal of Materials Science,* 33, 5487-5497.
5. Wilson, A. D. & McLean, J. W. 1988. *Glass-Ionomer Cement*, Quintessence Publishing Co.

Ionomer Glasses

- Fluoro-alumino-silicate glass
- Glass is designed to contain a similar ratio of Ca–P cations for bone formation (If heat-treated crystallises to apatite and mullite)
- Therapeutic release of fluoride anions by cement reduces the risk of secondary caries (dentistry) and stimulates bone deposition (orthopaedics)

Adhesion



Comparison between GIC and PMMA Cements

GIC	PMMA
• Chemically adhere to bone and dentin	• Mechanically adhere to bone
• No exotherms on setting	• Thermal necrosis of tissue due to large exotherms on setting
• No shrinkage of the cement	• Shrinkage due to polymerisation
• Therapeutic release of ions such as fluoride	• Chemical necrosis due to leaching of monomer

Adhesion

- Chemically bond to dentin and bone
- Formation of chemical complexes to substrate i.e. dentine, enamel, cortical and cancellous bone
- Bond to both the organic (collagen) and inorganic (apatite) components
- Adheres to any coherent oxide/passivating layer ie TiO_2, Cr_2O_3, NiO

Adhesion

GPA cement applications:

(1) restorative tooth filling materials

(2) luting cements (adhesives)
(3) Otological devices
(4) Crannio/Maxillofacial reconstruction**
(5) Alveolar ridge enhancement

GPA cements have the potential to be used as bone substitutes and cements

Deficiencies of Commercial GICs

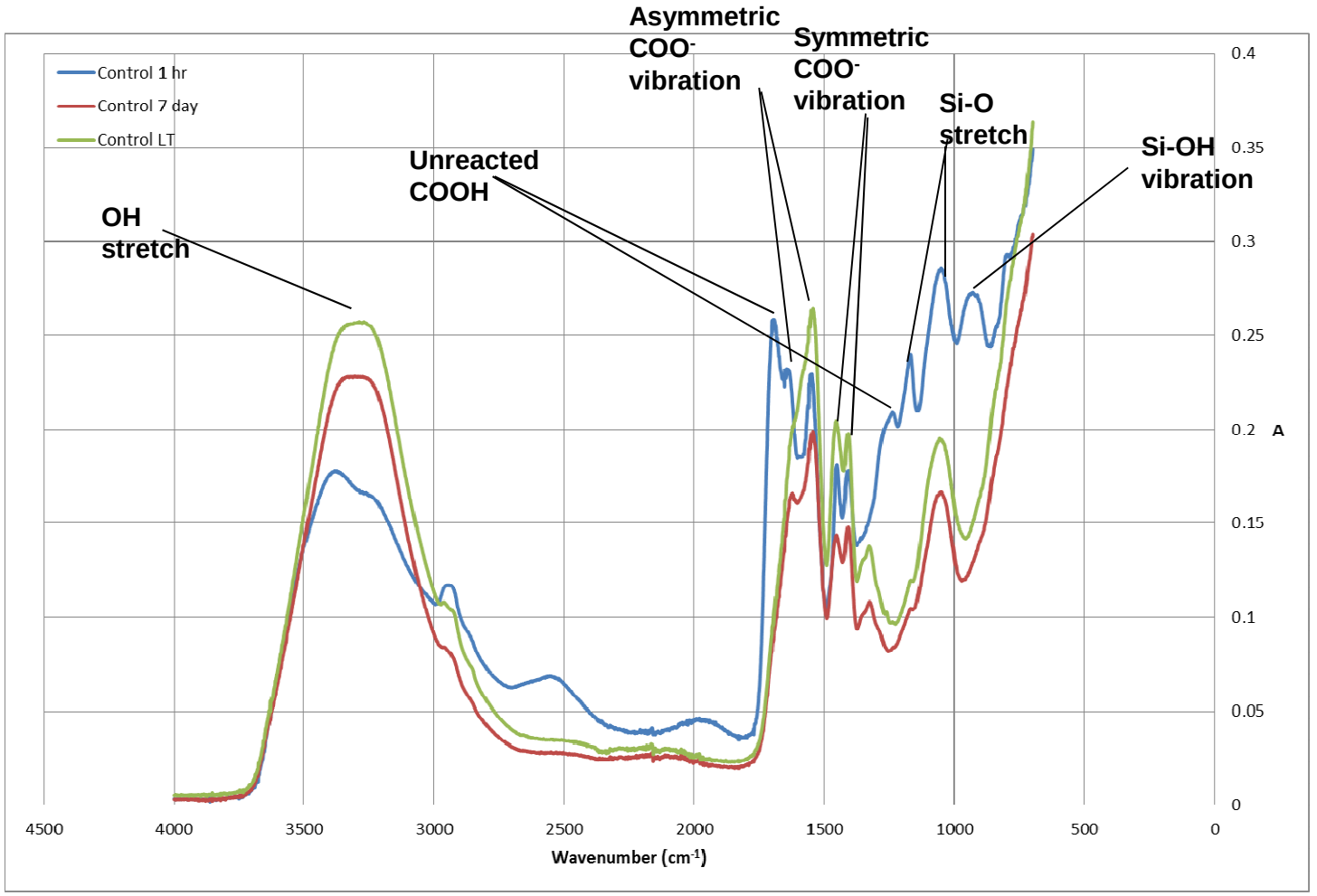
– Brittle material, lacks the toughness and fracture toughness for high load bearing applications

	Bone	GIC Commercial
Modulus	7 – 20 GPa	8 – 10 GPa
Toughness	1500 J/m^2	150 J/m^2
Fracture Toughness	0.5 – 2.2 MPa$\sqrt{m}$	0.5 – 0.9 MPa$\sqrt{m}$

Factors effecting GIC mechanical properties

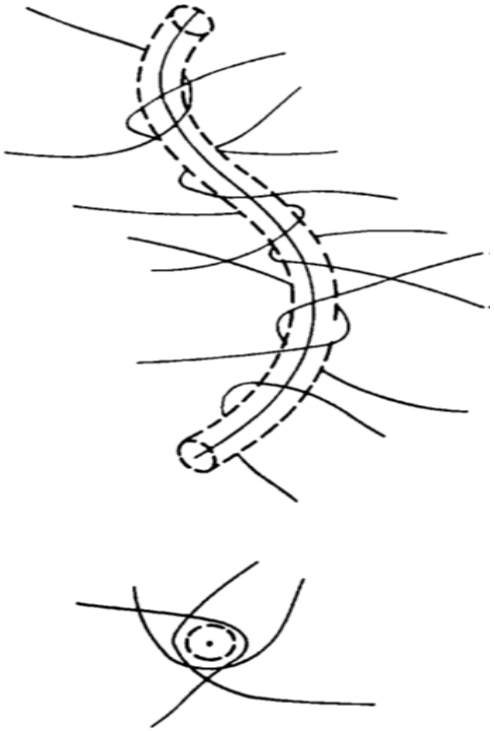
- Glass reactivity and composition
- PAA molecular weight
- Use of copolymers
- Particle size and morphology of powders
- Conditioning the glass particles

FTIR


Asymmetric COO- vibration
Symmetric COO- vibration
Si-O stretch
Si-OH vibration
Unreacted COOH
OH stretch
Control 1 hr
Control 7 day
Control LT
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
A
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Wavenumber (cm-1)

Fracture of GICs

- GICs exhibit thermoplastic polymer behaviour
- Reptation pull-out model by Prentice[8]
- Polymer chain trapped in a tube of entanglements formed by neighbouring chains
- $G \propto (M_n)^2$ this implies the slope should be 2

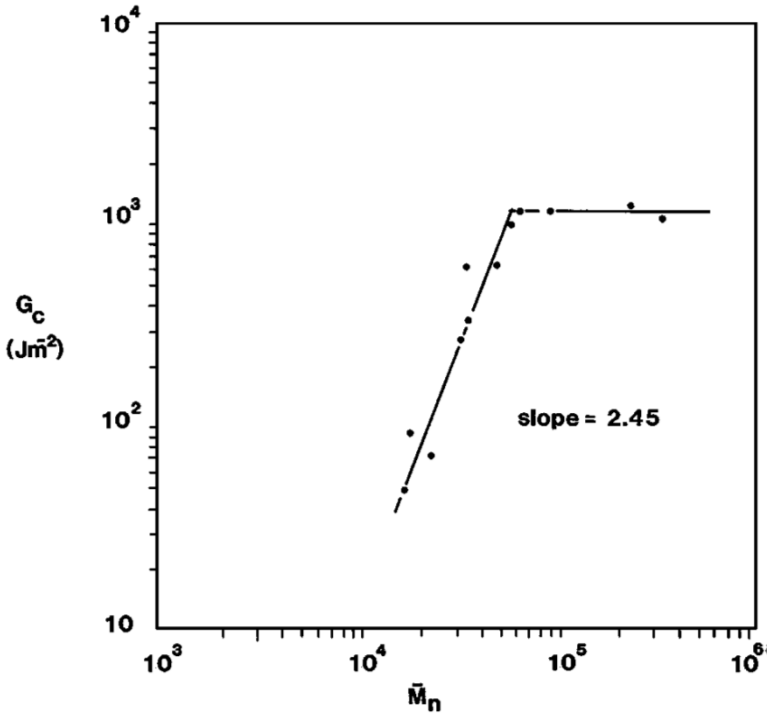


8. Prentice, P. 1985. The influence of molecular weight on the fracture of thermoplastic glassy polymers. *Journal of Materials Science*, 20, 1445-1454.

Fracture of GICs

Assumptions

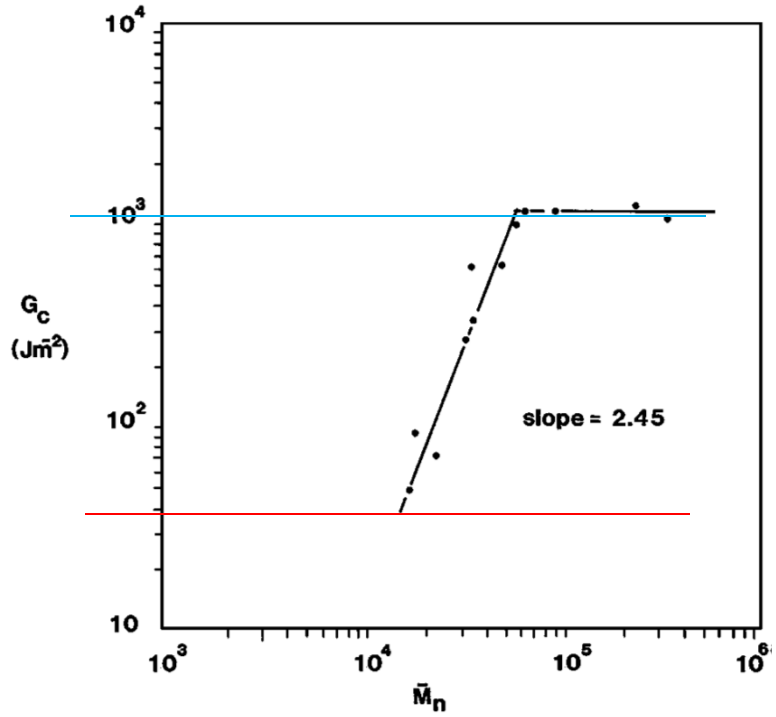
- Polymer crosses the fracture plane only once
- No distortion of the tube, distortion requires more work to remove the chain, increasing the plastic zone size
- Assumed that the polymer is monodisperse, whereas it has a polydisperse distribution



8. Prentice, P. 1985. The influence of molecular weight on the fracture of thermoplastic glassy polymers. *Journal of Materials Science,* 20, 1445-1454.

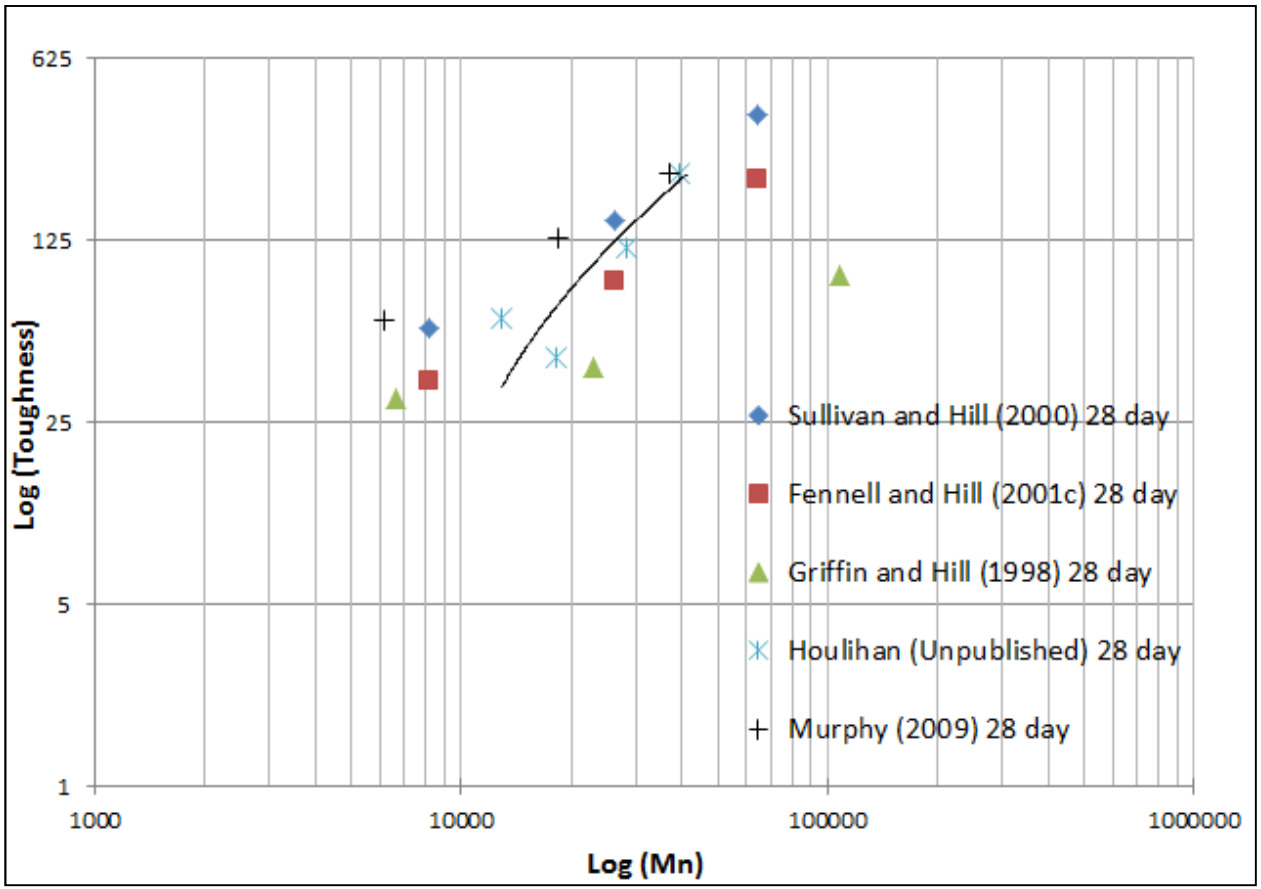
Fracture of GICs

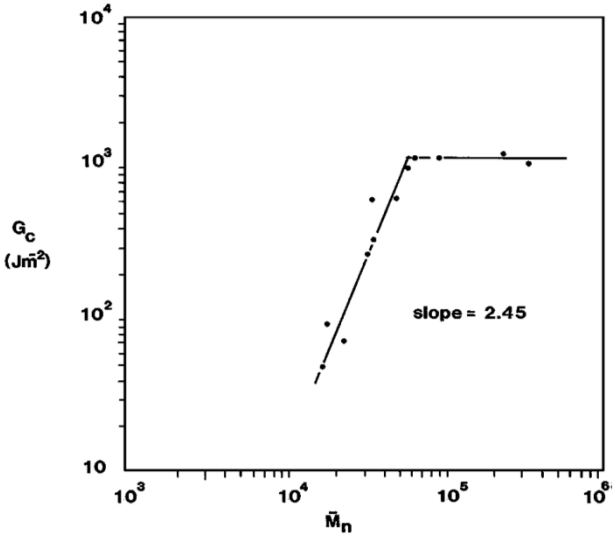
- Dependency of toughness on the M_n of the polymer
- Once the critical molar mass is reached, the toughness is independent of M_n
- Force to remove the chain from its tube is greater than that to break the C-C bond of the polymer backbone



Effect of M_n

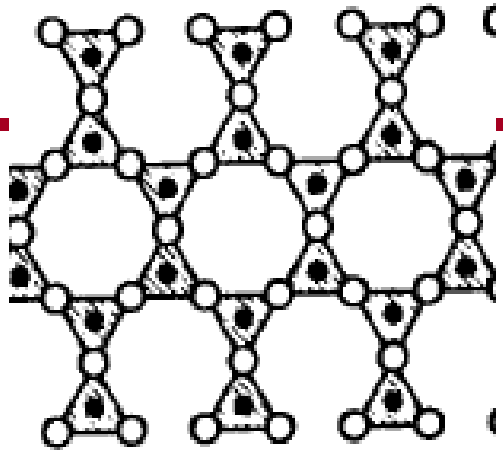
Toughness (G)



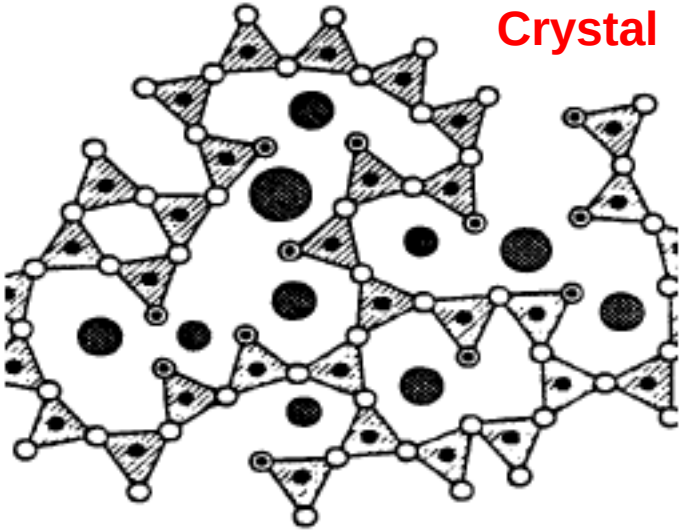


Glass Structure

- Crystal - Fixed Bond Angles and Distances. Regular Periodic Structure. Low Energy State.

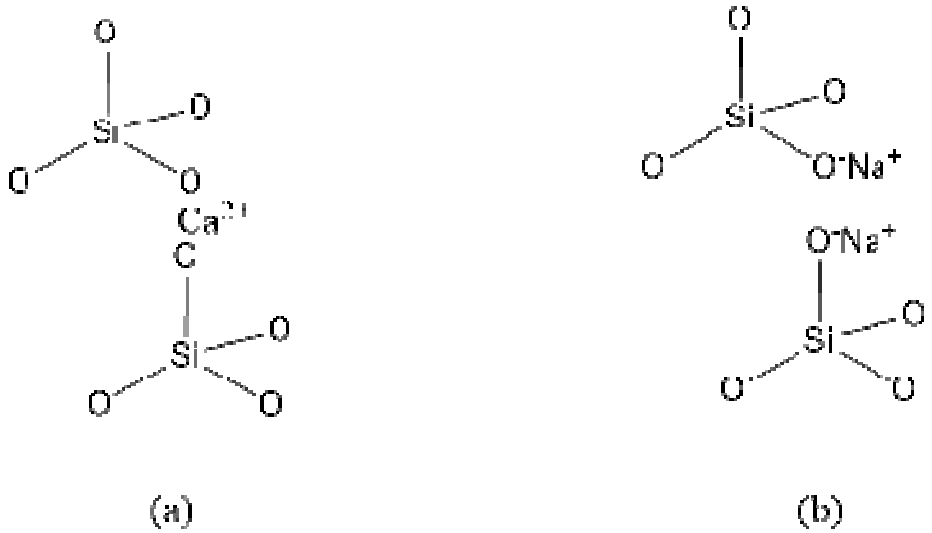


- Glass – Variation in Bond Angles and Distances. Disordered and High Energy State. Exhibits a Glass Transition.
- Produced by rapid quenching of a molten liquid.



Example Ionomer Glass -Sodium Series (1993!)

$1.5SiO_2$. $1.0Al_2O_3$ $0.5P_2O_5$. 1-XCaO.$0.5CaF_2$ XNa_2O
where X= 0.1, 0.2, 0.3 and 0.4.

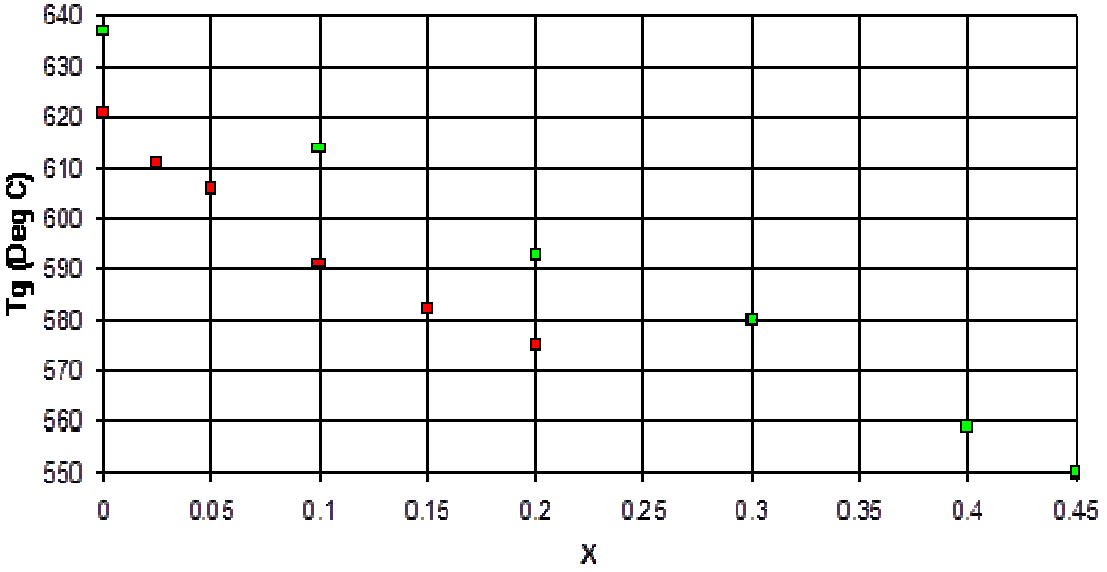


(a) (b)

Hypothesis: Replacement of structure on lhs by that on rhs would reduce Tg and increase reactivity. Many aspects of structure unknown at the time (role of F) – Properties difficult to interpret at the time

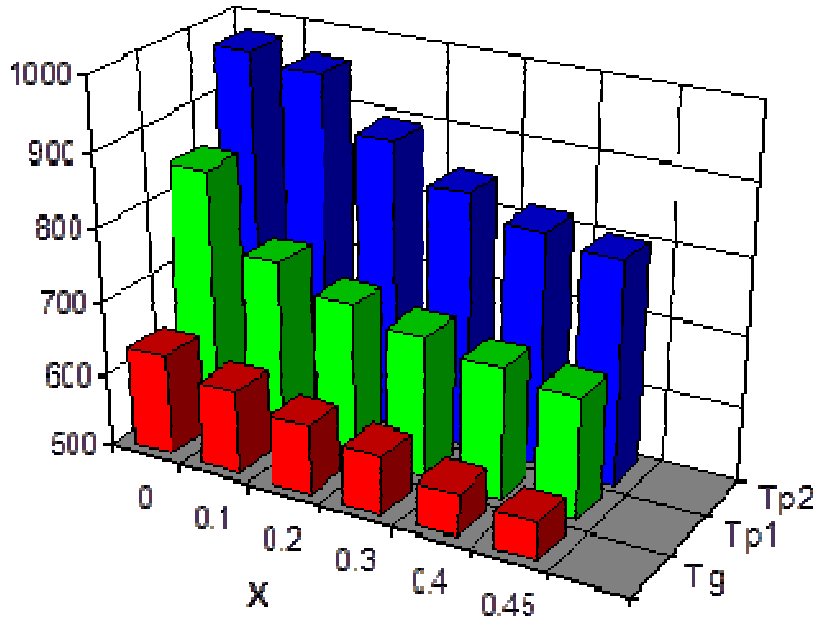
Example Ionomer Glass -Sodium Series

$1.5SiO_2$. $1.0Al_2O_3$ $0.5P_2O_5$. 1-XCaO.$0.5CaF_2$ XNa_2O
where X= 0.1, 0.2, 0.3 and 0.4. Na = Green, K = Red



Example Ionomer Glass -Sodium Series DSC

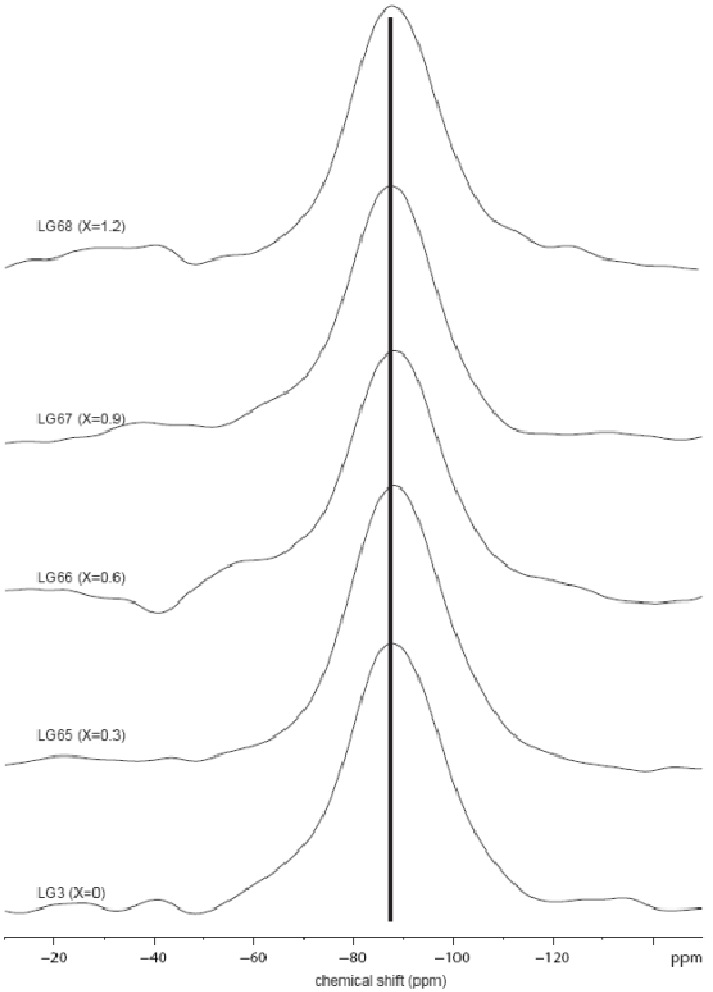
$1.5SiO_2$. $1.0Al_2O_3$ $0.5P_2O_5$. 1-XCaO.0.5CaF_2 XNa_2O



Glass Transition Temperatures and First and Second Peak Crystallisation Temperatures For $1.5SiO_2.O.5P_2O_5.Al_2O_3.XR_2O.(1\text{-}X)CaO.0.5CaF_2$ Glasses

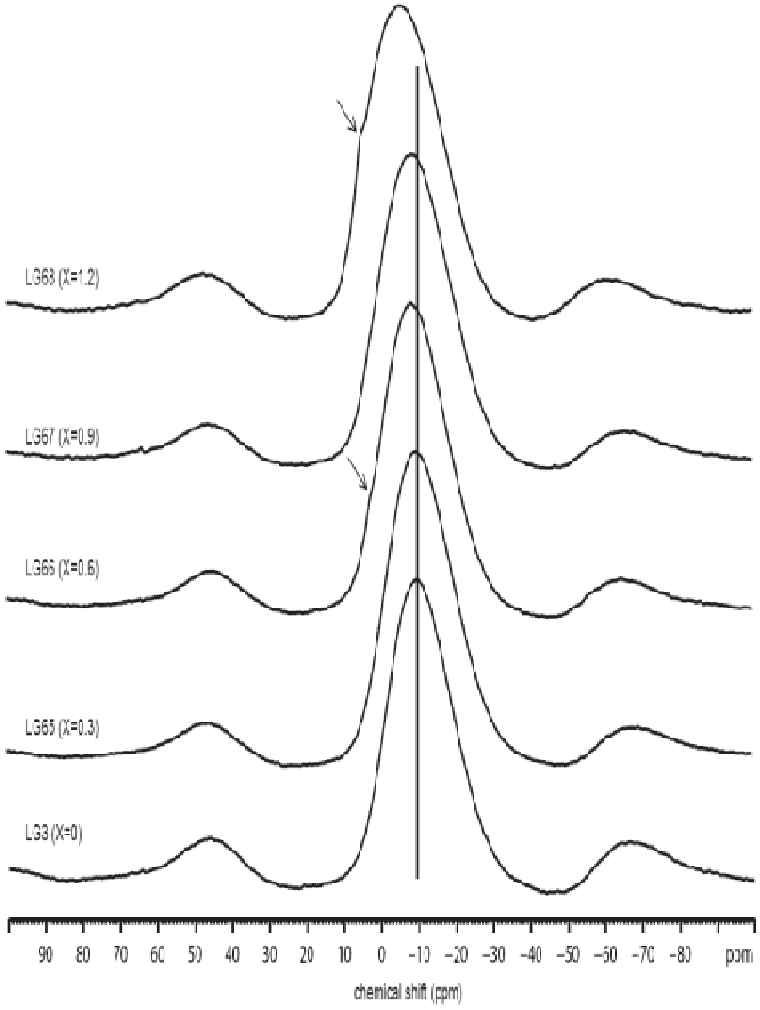
Example Ionomer Glass -Sodium Series ^{29}Si MAS-NMR

^{29}Si MAS-NMR spectra of sodium glasses
All glasses demonstrate the same chemical shift at around -87.0 to -88.0 ppm. Predominantly Q^3 structure, but unchanged by Na substitution



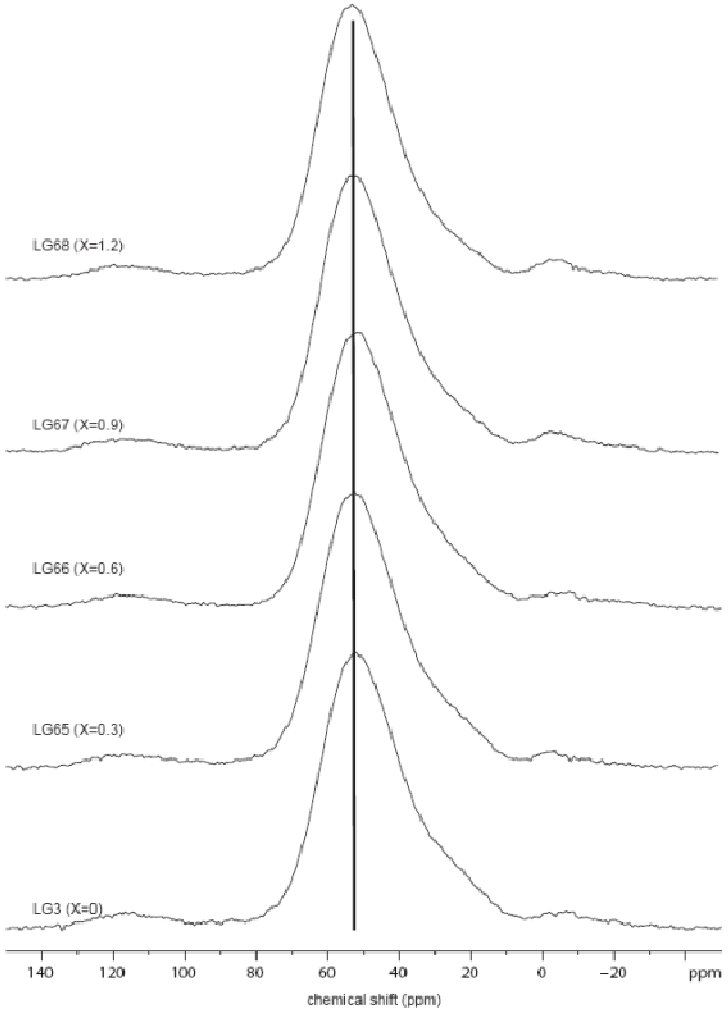
Example Ionomer Glass -Sodium Series ^{31}P MAS-NMR

^{31}P MAS-NMR spectra of sodium glasses of LG3, LG65, LG66, LG67 and LG68. Shows P is in Q^1 pyrophosphate role and with sodium increase shoulder appears (arrow) indicating some Q^0 orthophosphate formation



Example Ionomer Glass -Sodium Series ^{27}Al MAS-NMR

^{27}Al MAS-NMR spectra of sodium glasses The chemical shift remains the same for all the glasses. The major peak at around 52.0-53.0 ppm is Al(IV) and there is also a shoulder for Al(V) sites and a small peak at -2.0 ppm for Al(VI) sites. The line is a guide to the eye only

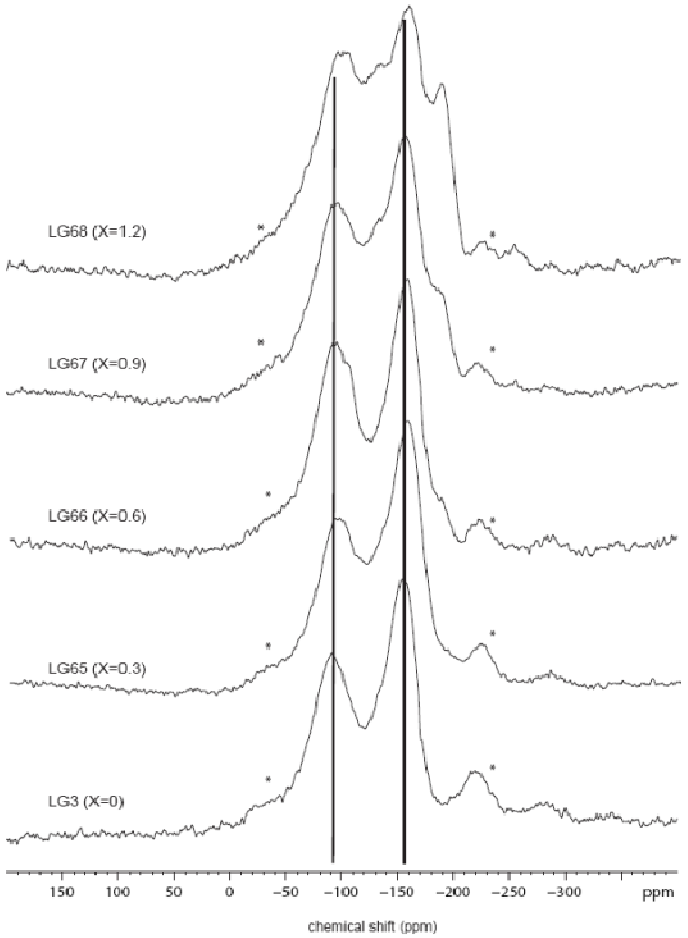


Example Ionomer Glass -Sodium Series

$1.5SiO_2$. $1.0Al_2O_3$ $0.5P_2O_5$. 1-XCaO.$0.5CaF_2$ XNa_2O

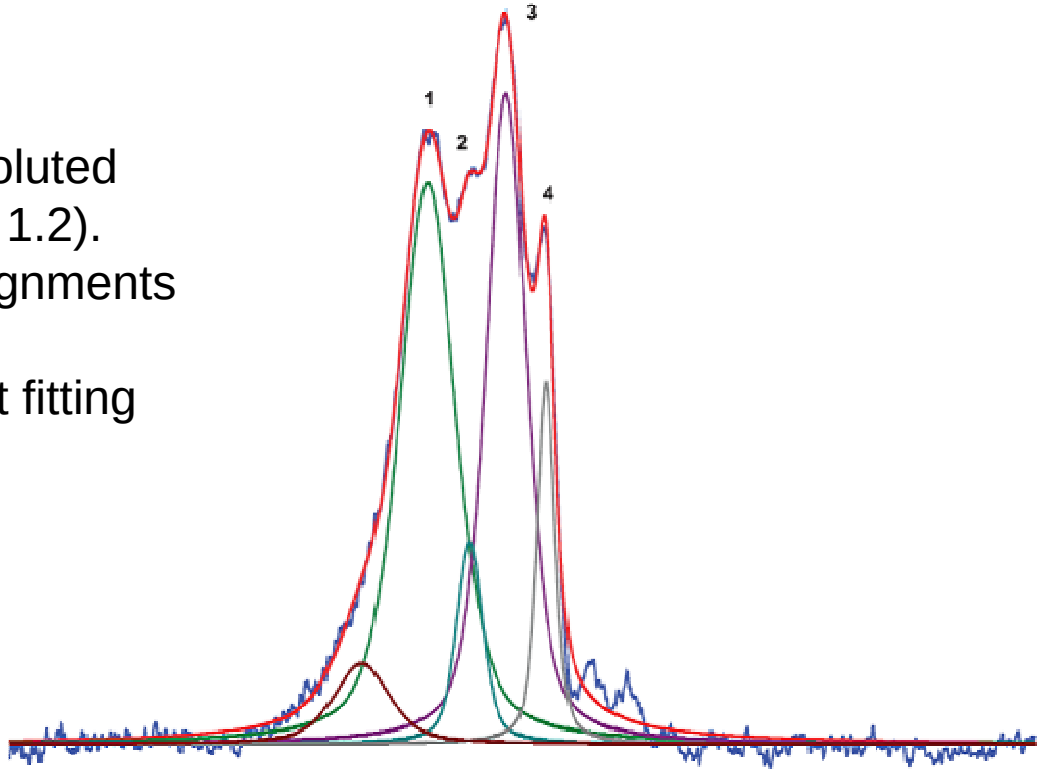
19F MAS-NMR spectra of sodium glasses of LG3, LG65, LG66, LG67 and LG68

There are two major peaks at -100.0 and -150.0 ppm corresponding to F-Ca(n) and Al-F-Ca(n). As the amount of sodium in the glass is increased, another two peaks appear at around -132.0 ppm which correspond to a mixed site of F-Ca/Na and at -186.0 ppm for Al-F-Na(n) site. The spinning sidebands are indicated by (*) and the lines are a guide to the eye only



Example Ionomer Glass -Sodium Series

The experimental and the de-convoluted spectra of the LG68 glass (Na_2O = 1.2).
Peak labels correspond to the assignments given in Table
Fittings were performed using dmfit fitting program Gaussian model



Example Ionomer Glass -Sodium Series

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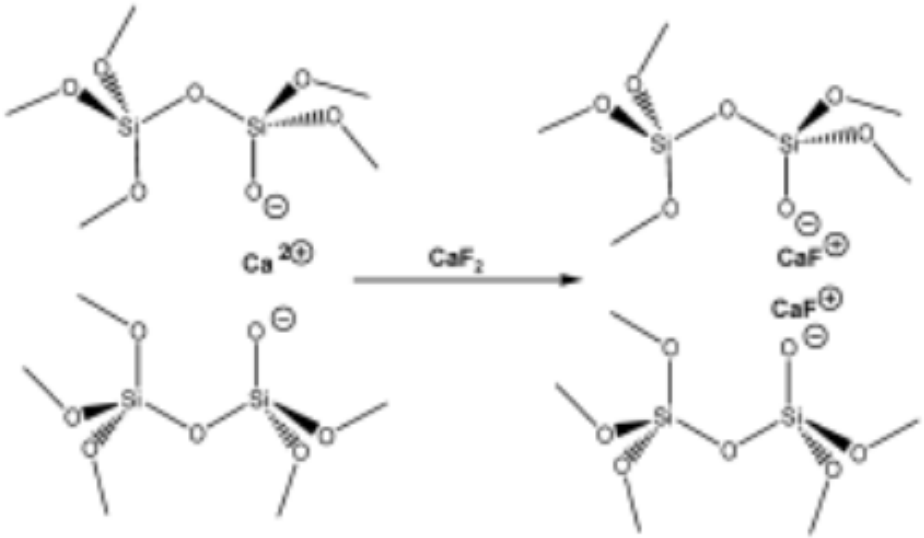


Example Ionomer Glass -Sodium Series

Conclusion:

Presence of fluorine in these glasses can be present as

- fluorine calcium complexes
- mixed fluorine calcium complexes
- non bridging fluorines as aluminium fluorine complexes charge balanced by either calcium or sodium.

Substitution of Ca by Na changes the ratio and type of these speciations

Structural roles in Ionomer and Bioactive Glasses

SiO_2
- increases network connectivity
- reduces bioactivity
- rate of network dissolution decreases

P_2O_5
- increases surface reactivity
- increases bioactivity
- increases degradation rate
- high conc's result in adverse effects

CaO, Na_2O
- reduce network connectivity

Structural roles in Ionomer and Bioactive Glasses

F
- increase bone formation at low conc's
- toxic at high conc's

Mg, K, B
- little effect on bioactivity

Al
- increases network connectivity
- can inhibit bone bonding
- increases resistance to ion exchange surface reactions
- interferes with osteoblast and fibroblast metabolism

Ta, Ti, Sb, Zr
- increase network connectivity

Predicting the bioactivity of glasses using the network connectivity or split network models

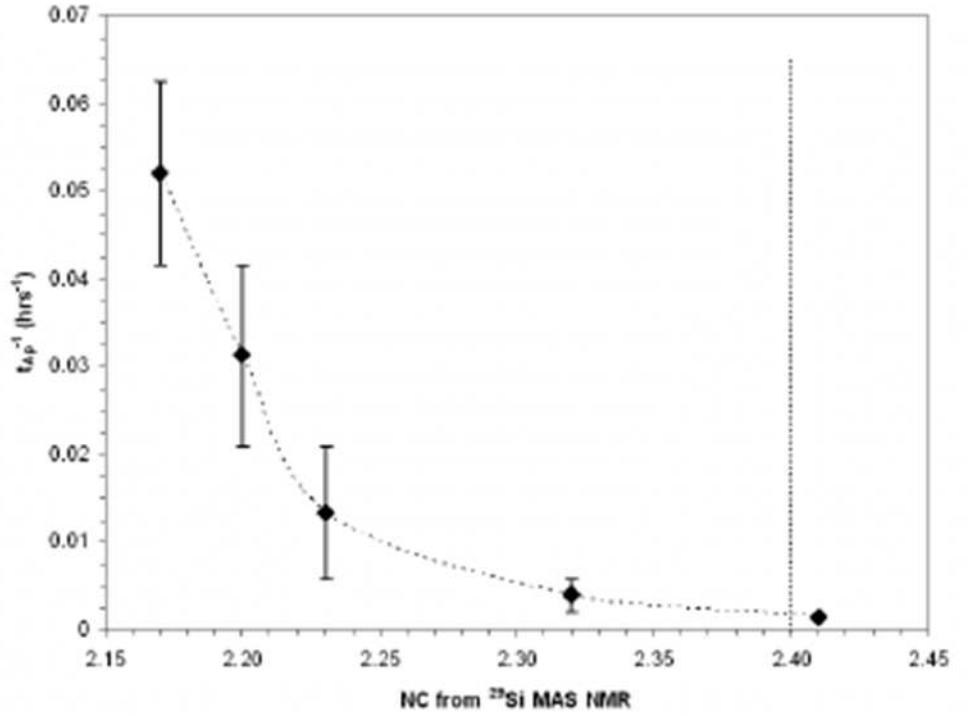
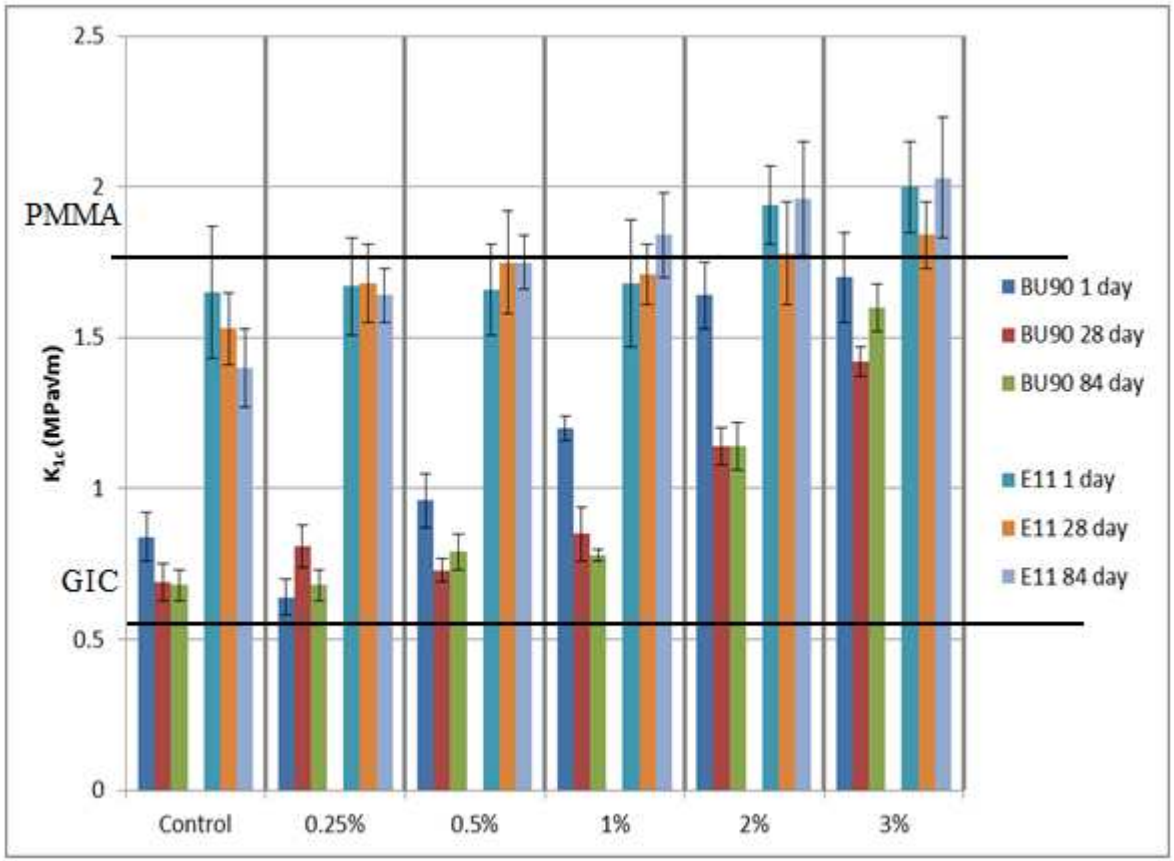


Figure 1: Bioactivity (defined as t_{Ap}^{-1}, where t_{Ap} is the time of first apatite formation in SBF as detected by XRD) of BG in the Mg series *vs.* NC_{NMR} calculated from the proportions of Q^2 and Q^3 silicons from ^{29}Si MAS NMR [11]. The vertical line represents the percolation point (NC = 2.4), i.e. the cut-off value for bioactivity as defined by Hill [7].

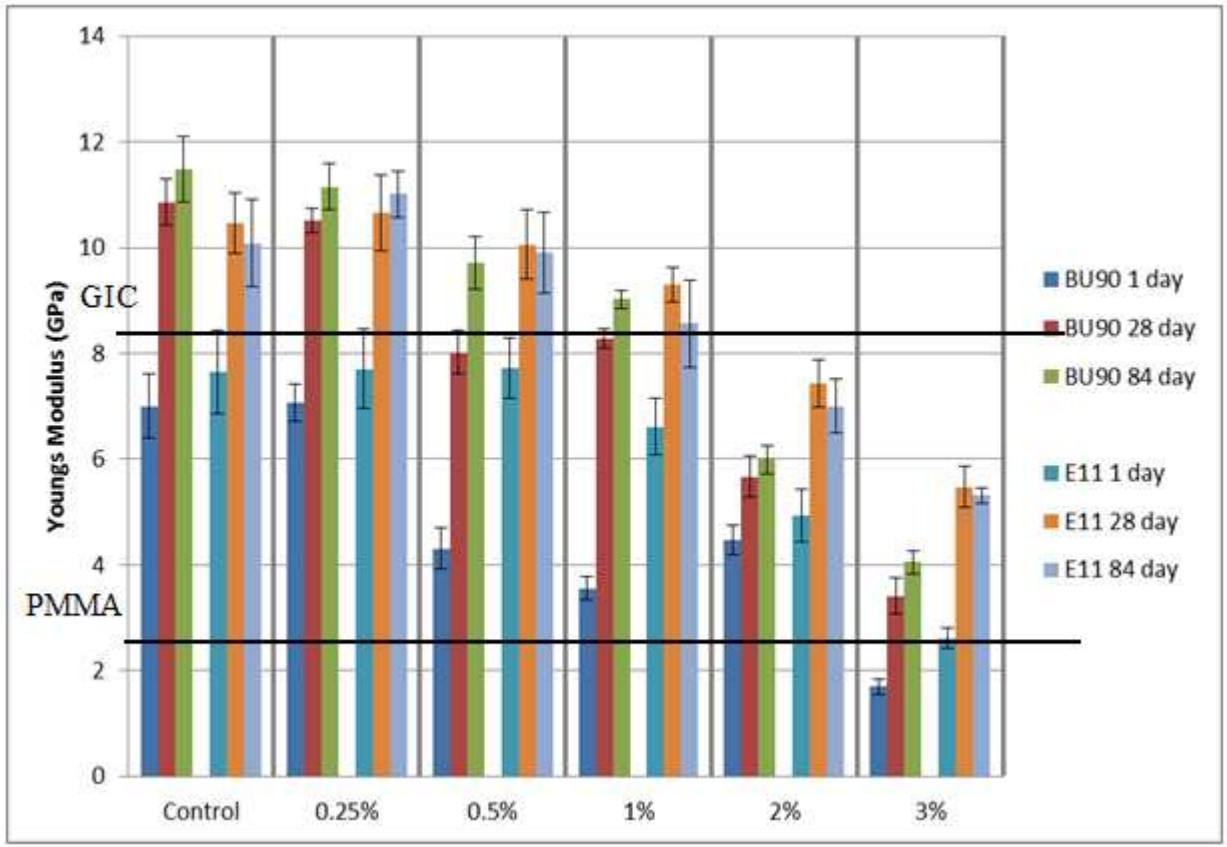
Robert G. Hill, Delia S. Brauer Journal of Non-Crystalline Solids 357 (2011) 3884–3887

Results



- K_{1c} of commercial GIC exceeded
- Matched K_{1c} of PMMA in some cases

Results



- Maintained E compared to GIC
- Matched E across formulations compared to PMMA

Mechanical data

	Cortical Bone	GIC from present study	Commercial GIC Fuji IX	PMMA
Fracture toughness (MPa√m)	6.4[1]	0.52 – 2.3	0.35 - 0.56[2]	1.82 - 3.52[5]
Young's Modulus (GPa)	15 – 30[3]	2.27 – 15.61	7 - 8[3]	1.90 - 2.28[5]
Toughness (J/m^2)	3400[1]	44.58 – 1281.75	40[2,3]	1521.58 – 5437.27[5]
Flexural Strength (MPa)	170[1]	14.1 – 53.5	17.8 – 51[2,4]	49.94 – 69.46[5]

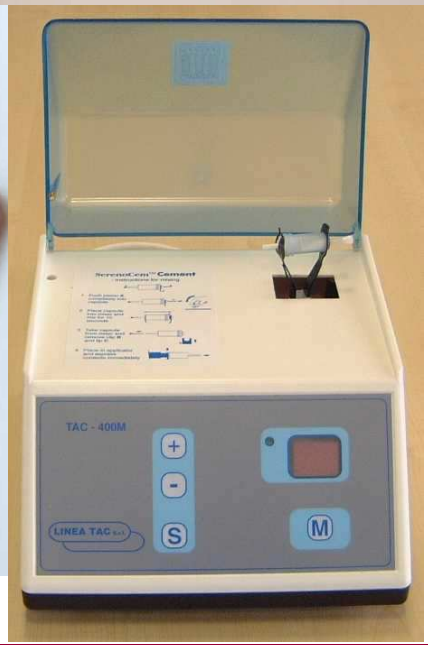
[1]Zioupos and Currey (1998) Changes in the stiffness, strength, and toughness of human cortical bone with age. Bone, 22, 57-66.
[2]Moshaverinia et al., (2010) Measure of microhardness, fracture toughness and flexural strength of N-vinylcaprolactam (NVC)-containing glass-ionomer dental cements. *Dental materials, 26, 1137-1143.*
[3]Ratner et al., (2004) Biomaterials Science: An Introduction to Materials in Medicine, Elsevier Science.
[4]Lohbauer et al., (2010) Dental Glass Ionomer Cements as Permanent Filling Materials – Properties, Limitations and Future Trends. *Materials,* 3, 76-96
[5]Chilikina (unpublished) personal communication

Example Ionomer Glass –Fluoride Series

$$1.5SiO_2\ Al_2O_3\ 0.5P_2O_5\ CaO\ XCaF_2$$

GLASS CODE	X
LG45	0.00
LG44	0.25
LG3	0.50
LG26	0.66
LG2	0.75
LG42	1.00

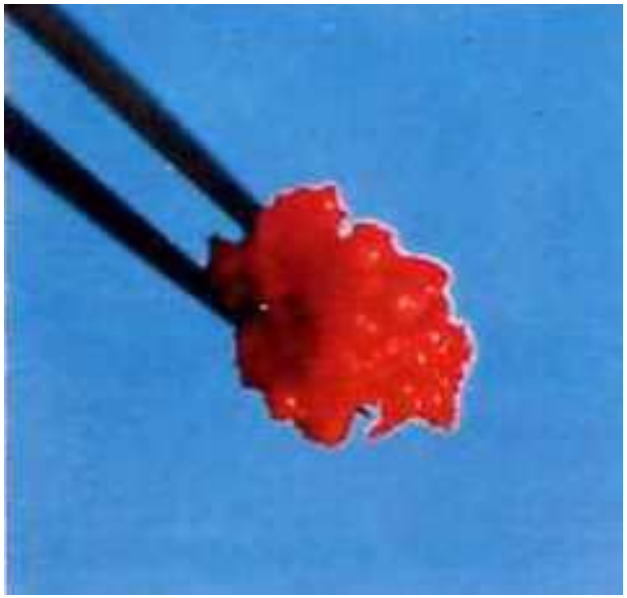
Serenocem™ Capsules



$1.5SiO_2\ Al_2O_3\ 0.5P_2O_5\ CaO\ XCaF_2$

Serenocem™ Granules

EM scan of granules, showing micro pores. magnification x 20



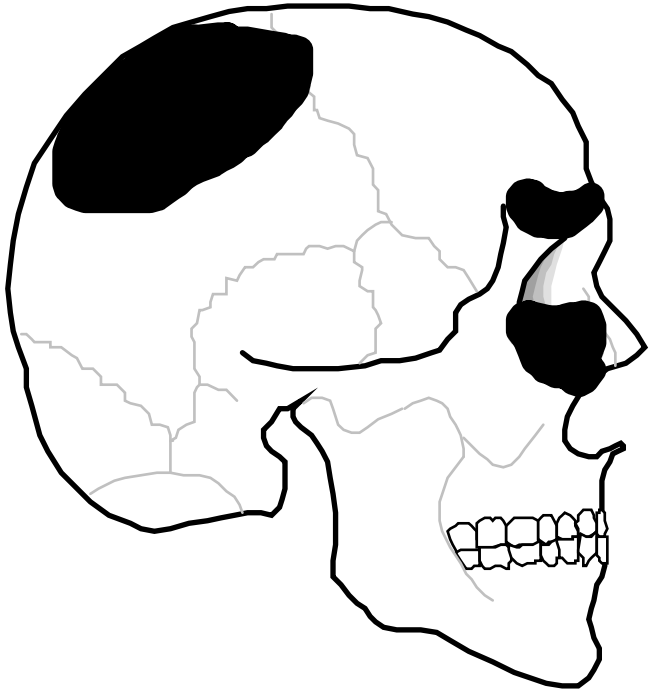
Hydrophilic granules absorb blood to produce fibrin clot.

Produced by incorporating $CaCO_3$ into the cement which generates CO_2 in-situ, foaming the cement . Sold as a cancellous bone substitute.

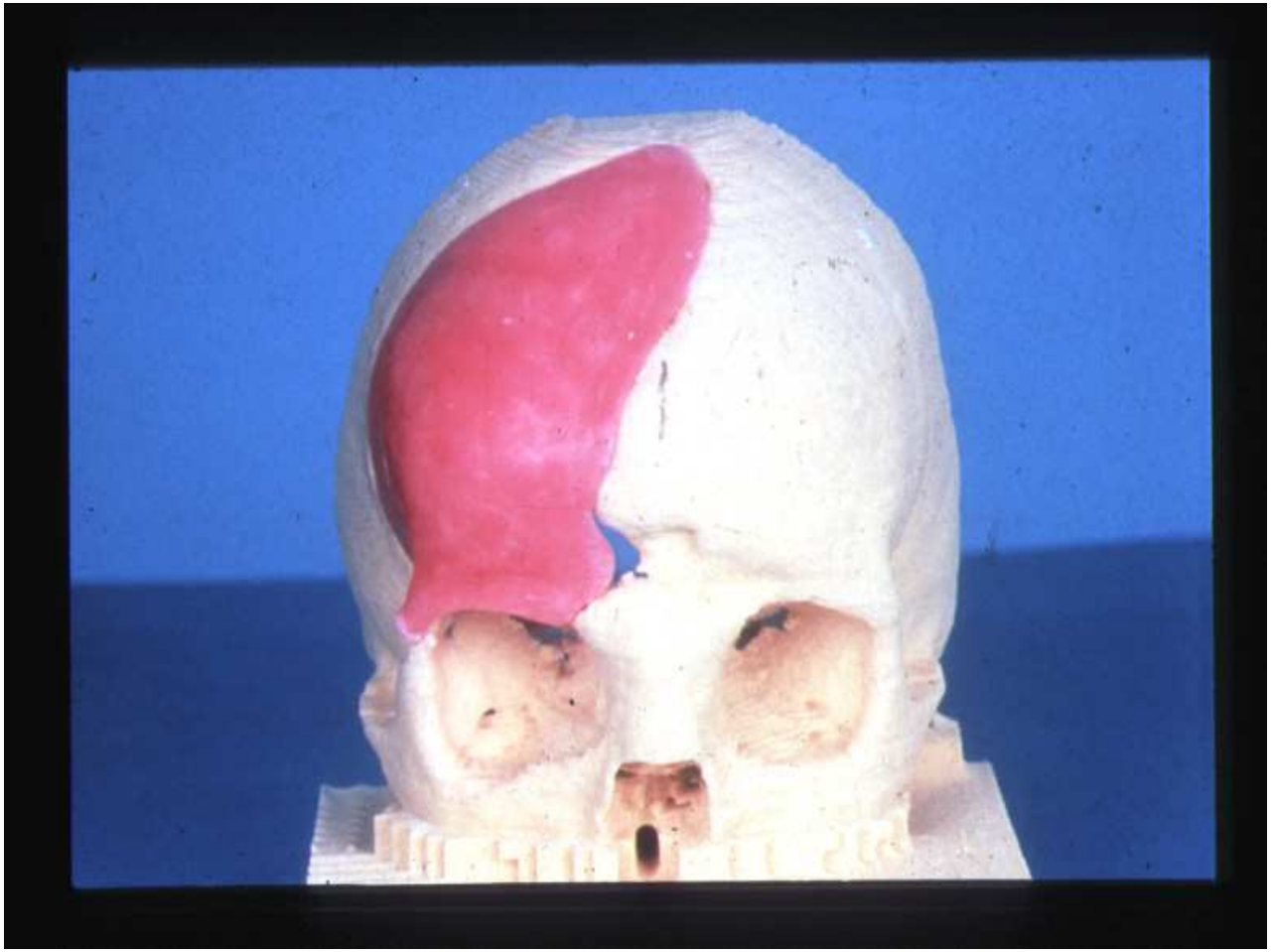
GPA Cement BONE SUBSTITUTES

e.g. (a) Cranial bone plates

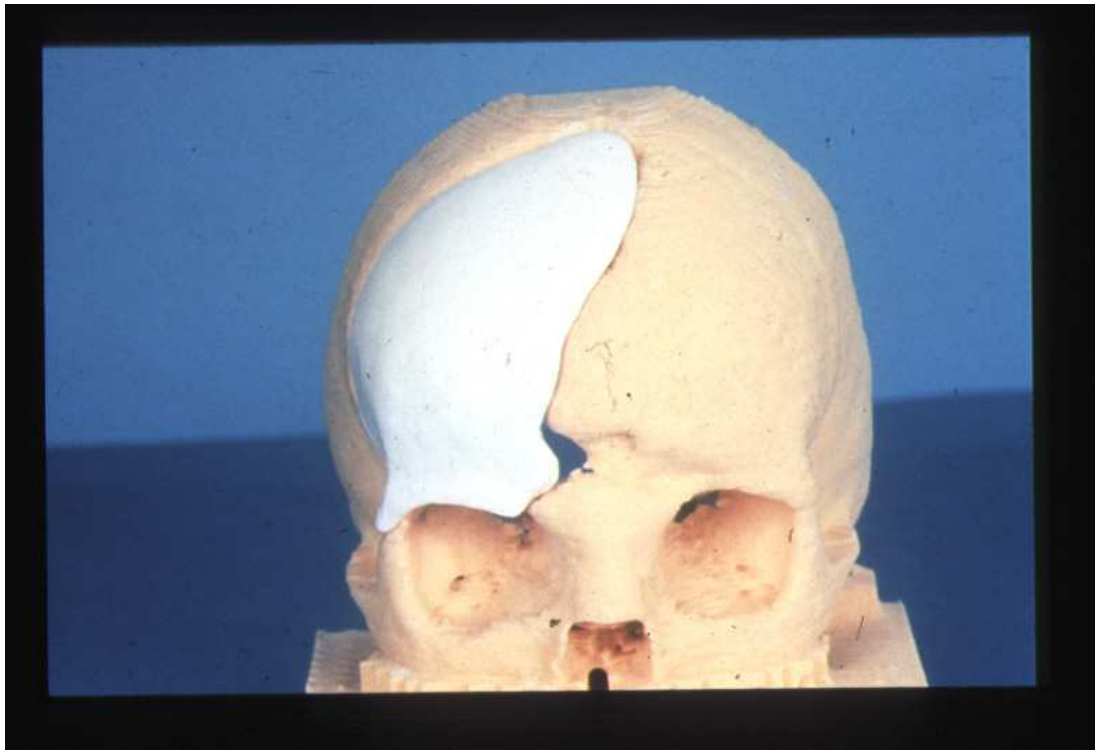
(b) Maxillofacial implants



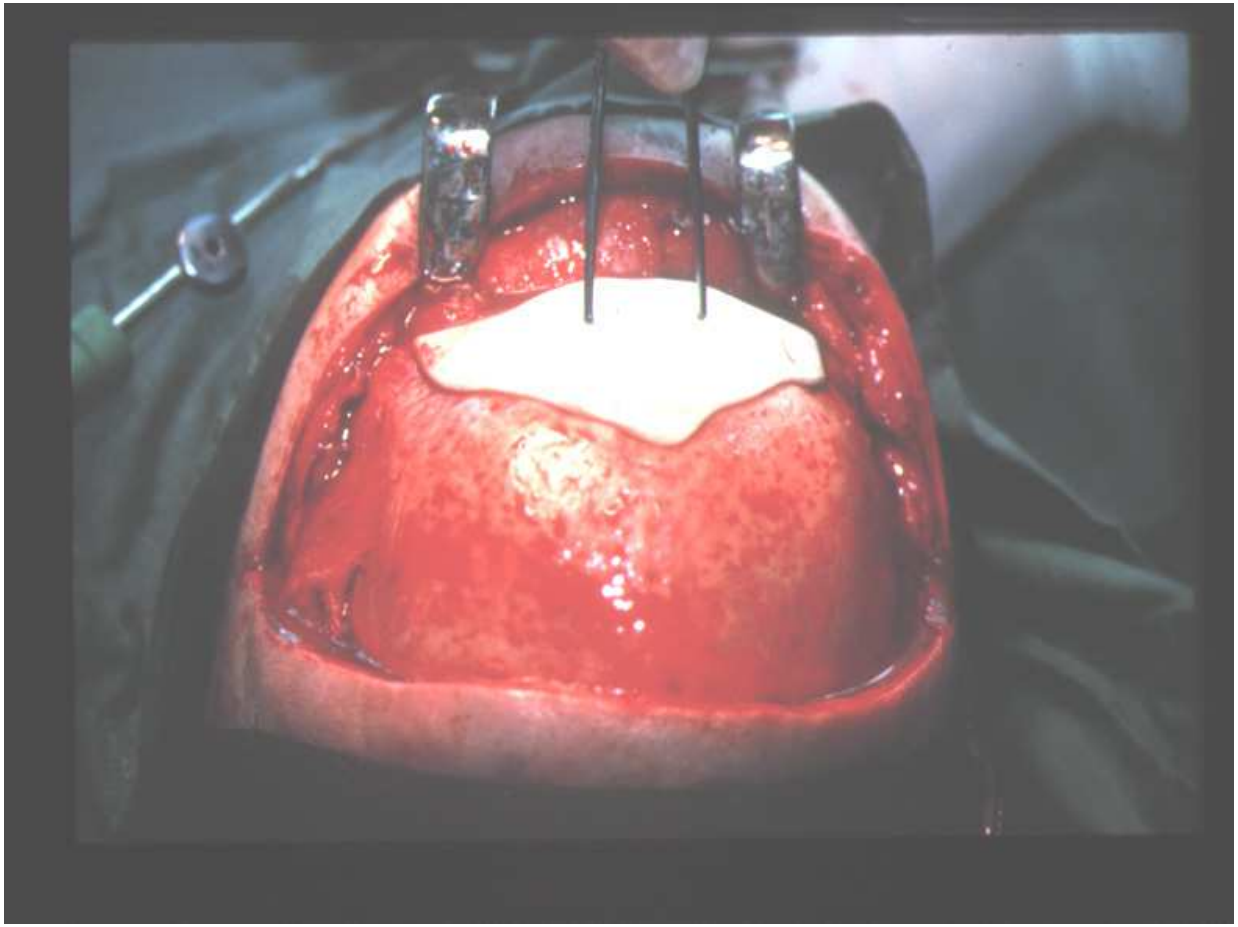
Wax Impression formed via CAT Scan



Custom Plate formed + Autoclaved



Placement of GI Cranial Plate



NB This product off market

Glass Ionomer cements

- Advantages
    - Non-exothermic setting reaction
    - Adhesive bond formed with bone and metals
    - Bioactive ions incorporated
    - Low systemic toxicity
    - Reduced local toxicity
- Disadvantages
    - Inferior mechanical properties
    - Neurotoxicity of Aluminium and PAA