

Mechanical properties of aramid fibre-reinforced acrylic bone cement

The use of polymethylmethacrylate (PMMA) as a method of prosthetic fixation has found wide acceptance. However, the number of prostheses removed because of fracture of the surrounding PMMA cement is significant [1]. Methods of improving the mechanical behaviour of bone cement have included reinforcement with metal wire [2] and carbon fibres [3, 4] and formation of a porous cement to allow bone ingrowth [5]. The problem with many such methods has been the tedious mixing techniques involved. The objective of the present study was to examine the strength and fracture properties of a fibre-reinforced bone cement mixed in much the same manner as unreinforced cement.

Standard tensile and compact tension fracture toughness (ASTM standard E399-74T) specimens were moulded using Kevlar 29 aramid fibres (E. I. DuPont De Nemours & Co) and PMMA powder and monomer (Kerr-Sybron Corp). Although Kevlar fibre was not developed for medical or surgical purposes, implantation studies with dogs have shown it to have a biocompatibility comparable to Dacron [6]. The weighed fibres (average length = 1.3 cm) were mixed with the powder and the requisite volume of monomer added. Three concentrations (1.0, 4.0 and 7.0 wt%) of fibre were used with eight tensile and eight fracture toughness specimens moulded from each concentration. Concentrations higher than 7% were difficult to mix. In addition to the three concentrations used, eight tensile and eight fracture toughness specimens without fibres were also moulded.

Both tensile and fracture toughness tests were conducted at a rate of 147 N sec^{-1} on an MTS servohydraulic test system. For fracture toughness tests, a clip gauge was used to measure the crack opening displacement. From the tensile tests, mean values (\pm S.E.) of ultimate strength and elastic modulus were obtained for each fibre concentration plus controls (Table I). Fig. 1 shows mean values (\pm S.E.) of ultimate strength plotted against the weight % of fibre, demonstrating a statistically significant ($r = 0.53$, $P < 0.01$) positive correlation between strength and fibre concentration. Mean values (\pm S.E.) of fracture toughness were obtained from load versus crack opening dis-

TABLE I Summary of strength and fracture properties

Wt% fibre	Tensile strength (MN m ⁻²)	Fracture toughness (MN m ^{3/2})
Control	30.8 \pm 1.6*	1.53 \pm 0.08
1.0	36.1 \pm 2.3	1.88 \pm 0.06
4.0	38.2 \pm 1.2	2.31 \pm 0.13
7.0	42.8 \pm 3.8	2.85 \pm 0.15

*Each datum point is the mean (\pm one S.E.) of eight specimens.

placement curves (Table I). A significant ($r = 0.84$, $P < 0.001$) positive correlation between fracture toughness and fibre content was also found (Fig. 2).

The tensile strength values for the control specimens agree well with reported values [7]. Likewise, the 0 wt% fracture toughness values agree well with the literature [8]. The increase in strength with 7% addition of aramid fibres is approximately a third that found with additions of 2 vol% carbon fibres [4] or with chrome-cobalt alloy wires comprising 6% of the cross-sectional area [2]. Strength approaching those found with graphite or metal reinforcement could possibly be

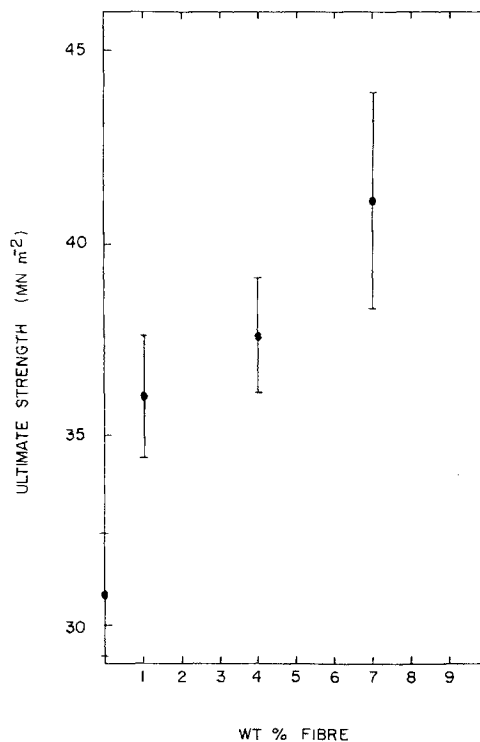


Figure 1 Ultimate tensile strength plotted against wt% fibre. Each datum point is the mean (\pm S.E.) of eight specimens.

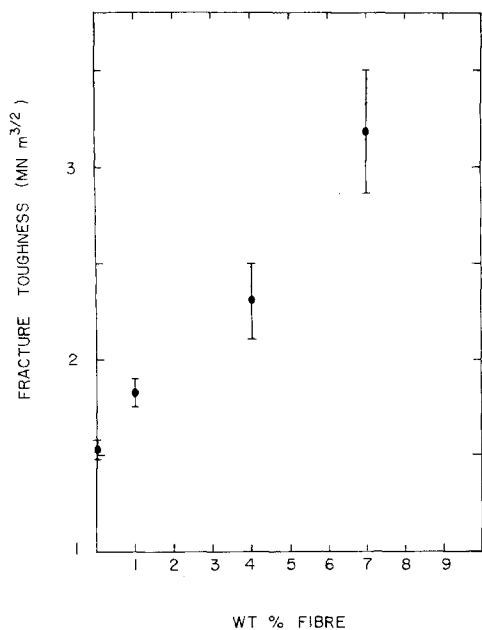


Figure 2 Fracture toughness plotted against wt% fibre. Each datum point is the mean (\pm S.E.) of eight specimens.

reached by using greater percentages of aramid fibres, but such large additions make mixing the cement more difficult. More importantly, such large increases in strength may not be necessary to eliminate the problems of cement breakdown. Even if such strength increases were achievable they may be undesirable in that the associated increase in stiffness could be detrimental to the transmission of load from a prosthesis to the surrounding bone.

Fracture surfaces from both tensile and fracture toughness specimens were sputter-coated with approximately 200 Å of gold-palladium compound and viewed in the scanning electron microscope. Upon examination, the aramid fibres appeared unwetted by the PMMA cement (Fig. 3). Fibres protruded from the fracture surfaces of both types of specimens, but were more oriented normal to the fracture surface in the tensile specimens than in the fracture toughness specimens in which fibres were more randomly oriented. In both types of specimens fibres were often bunched together (Fig. 4) as a result of poor mixing. The same problem has been shown to occur in the carbon fibre-reinforced cement [4] and may account for much of the scatter in the results of this and other investigations.

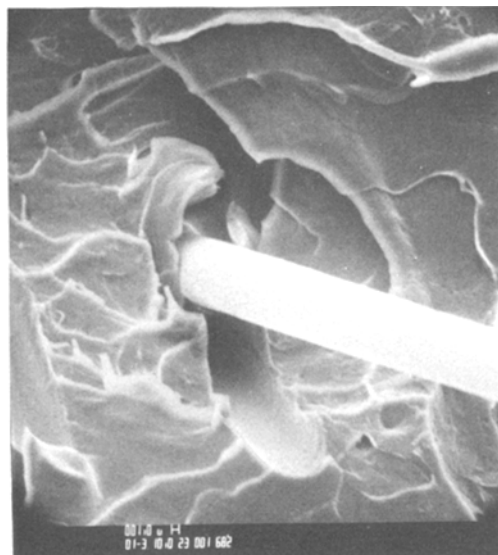


Figure 3 Scanning electron photomicrograph of the fracture surface of a tensile specimen showing unwetted fibre protruding from the surface.

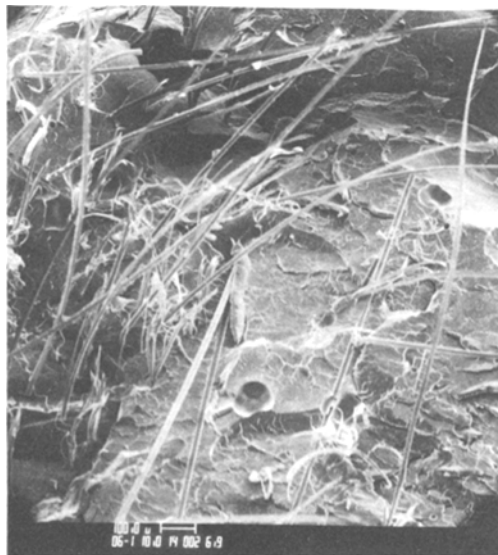


Figure 4 Scanning electron photomicrograph of tensile specimen fracture surface showing bunching of fibres.

In conclusion, the addition of Kevlar aramid fibres to PMMA bone cement significantly enhances the elastic modulus and tensile strength of the cement. The addition of 7 wt% fibre, for example, resulted in a 32% increase in strength and a 74% increase in fracture toughness. These results were obtained without altering the mixing technique commonly used with bone cement.

Acknowledgement

This work was supported by a grant from the Rehabilitation Services Administration, Department of H.E.W. (No. 23-P-57377/2-02).

References

1. F. A. WEBER and J. CHARNLEY, *J. Bone and Jt. Surg.* **57B** (1975) 297.
2. J. P. TAITSMAN and S. SAHA, *ibid* **59A** (1977) 419.
3. A. KNOELL, H. MAXWELL and C. BECHTOL, *Ann. Biomed. Eng.* **3** (1975) 225.
4. R. M. PILLIAR, R. BLACKWELL, I. MACNAB and H. U. CAMERON, *J. Biomed. Mater. Res.* **10** (1976) 893.
5. A. M. RIJKE, M. R. RIEGER, R. E. MCLAUGHLIN and S. MCCOY, *ibid* **11** (1977) 373.

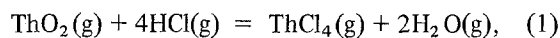
6. R. H. HUXTER, S. H. JAEGER and J. M. HUNTER, *Trans. 23rd Ann. ORS* **2** (1977) 108.
7. E. P. LAUTENSCHLAGER, B. K. MOORE and C. M. SCHONFELD, *J. Biomed. Mater. Res.* **8** (1974) 185.
8. T. A. FREITAG and S. L. CANNON, *ibid* **11** (1977) 609.

Received 12 June
and accepted 21 July 1978.

T. M. WRIGHT
P. S. TRENT
*Department of Biomechanics,
The Hospital for Special Surgery,
New York, New York, USA*

Preparation of ThSiO₄ single crystals by a vapour phase reaction

Thorium silicate is the only ternary compound which exists in the ThO₂ and SiO₂ system [1, 2]. Thorium silicate single crystals were synthesized by the reaction of an aqueous solution of thorium chloride with pyrex glass [3]. The present paper reports a similar process for the preparation of ThSiO₄ crystals using a vapour phase reaction. In the study of chemical transport reactions of uranium and thorium oxides the author has prepared single crystals of ThSiO₄ using halogen gases [4]. When ThO₂ source material is sealed in a quartz tube with HCl or Cl₂ gas as a transport agent and placed in the hot zone, ThSiO₄ single crystals can be produced almost in the cold zone in the quartz tube. The crystal is about 1 × 0.7 × 0.5 mm³ in size and is transparent with many faces. The possible reactions are considered as follows:



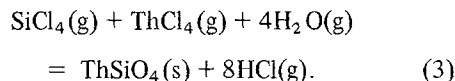
some parts of ThCl₄(g) would react with the quartz tube,



and then the formation of ThSiO₄ crystals proceeds in the colder zone as,

TABLE I Preparation conditions of ThSiO₄ crystals

	ThO ₂ + HCl	ThO ₂ + Cl ₂
Source temperature (°C)	1050	1050
Deposition temperature (°C)	950	950
Pressure of halogen (atm at 1000° C)	3.49	1.56
Transport time (h)	347	936
Transport rate (mg h ⁻¹)	0.17	0.26
Crystal size (mm ³)	0.2 × 0.2 × 0.2	1 × 0.7 × 0.5



Evidence that ThSiO₄ crystals may be prepared using a vapour phase reaction (Equation 3) is due to the facts:

(1) ThSiO₄ crystals can be produced in the cold zone more readily than in intermediate or hot zones.

(2) The crystals produced are randomly distributed in the cold zone as is usual in the case of chemical transport reactions, and not uniformly deposited all over the tube, as is the coating produced by the direct reaction of ThCl₄(g) with the quartz tube.

When the temperature at the cold zone is below