# Experimental Compression Tests on Orthopedic Bone Cement used in Total Hip Replacement

**LUCIAN BOGDAN[1]*, CRISTIAN - SORIN NES[1]*, DIANA DUCAN[2], JENEL MARIAN PATRASCU[3]**

[1]Politehnica University of Timisoara, Mechanics and Strength of Materials Dept., 1 M. Viteazu Blvd., 300222, Timisoara, Romania
[2]William Shakespeare High School, 6 I. L. Caragiale Str., 300104, Timisoara, Romania
[3]Victor Babeş University of Medicine and Pharmacy, 2 Eftimie Murgu Sq., 300041, Timisoara, Romania

*The paper presents the results of compressive tests performed on Biomet® orthopedic bone cement currently used in arthroplasty. By direct molding of the cement, cylindrical test specimens were manufactured with cross section diameter of 6 mm and height of 12 mm. The stress–strain curves of all specimens tested exhibited similar linear elastic regime with a local maximum followed by yielding. The average compressive strength of the samples is 91.55 MPa, while the average modulus of elasticity was calculated at 1483 MPa. The obtained results can be used in order to asses the fatigue life-time of this type of bone cement.*

*Keywords: total hip replacement, bone cement, PMMA, compression, elastic modulus, Poisson's ratio*

Acrylic bone cement based on PMMA (polymethyl methacrylate) is used for the fixation of joint implants since the 1960s, after being popularized by Charnley [1]. The basic function of bone cement is to transfer the loads between bone and implant, in order to obtain an optimal distribution of contact stresses in the reconstructed joint. As of 2005, more than 60 types of bone cement have been used for the treatment of joint diseases and bone fractures [2, 3].

Long term failure of the implant occurs if generated stresses exceed the capability of the bone cement to maintain the optimal load transfer [4]. In case of total hip replacement, the primary mechanical factors that lead to failure of the cemented hip implants are: loosening of the femoral component (stem) of the implant, fatigue wear that produces microcracks inside the cemented mantle, contact area and penetration depth of the cement inside the bone, local stress concentrations at the implant-cement-bone interface as a result of loads and moments developed during normal activities [5,-10]. Biologically, the fracture of the cemented mantle produces cement particles that increase bone resorbtion and lead to various biological responses depending on particle shape and size. Approximately 75% of all revisions of cemented total hip replacements are caused by this type of failure [11, 12]. Furthermore, reaction to wear particles and infections is an important issue [13, 14].

To assess the long term behaviour of the bone-cement-implant interface, finite element analysis (FEA) can be used. FEA models are based on accurate representations of geometric data (e.g. bone-cement-prosthesis geometry), material properties, boundary conditions and applied loads.

Mechanical properties of bone cements have been reported by many research groups; unfortunately, the literature relating to the mechanical properties of bone cements cannot be compared because of a series of factors that influence the obtained results. Some of the factors that influence these properties are the composition of the cement [15], the addition of radiopacifying agents and antibiotics [16], porosity [17], the sterilization method used for the polymer powder and the liquid monomer components [18], the mixing methods [19], the environmental test conditions [20] and specimen design.

This paper presents experimental compression tests in order to determine the material properties of a specific bone cement currently used in orthopedic surgery. The obtained results can be used in FEA models of the hip joint arthroplasty.

## Experimental part

### *Materials and methods*

In the study of bone cement properties, the obtained results depend on the sensitivity of test sample preparation, testing rate and testing environment. All these factors are documented to influence the mechanical properties of bone cement; therefore in this study we used standardized test methods.

High viscosity bone cement, produced and supplied by Biomet® (*Biomet Orthopedics, Dietikon, Switzerland*) as polymer powder (44 g) and monomer liquid (18,8 g) portions were used. Table 1 presents the chemical composition of this type of bone cement.

Liquid and powder portions of the cement were chosen according to the manufacturer instructions. All of the test specimens were prepared using hand mixing techniques and molded into the final shape at ambient temperature (23°C). Hand mixing techniques were chosen because total hip arthroplasty usually involves hand mixing the bone cement by the surgeon prior to injection into the femoral tunnel.

**Table 1**
CHEMICAL CONTENT OF BIOMET POWDER AND LIQUID COMPONENTS

| Composition of bone cement powder | |
|---|---|
| Poly(methyl acrylate, methyl methacrylate) | 38,3 g |
| Zirconium dioxide | 5,3 g |
| Benzoyl peroxide | 0,4 g |
| Composition of bone cement liquid | |
| Methylmethacrylate | 18,4 g |
| N,N-dimethyl-toluidine | 0,4 g |

* *email: blucian85@gmail.com; cristianedonis@yahoo.com*

The liquid and powder components were mixed using sterile and inert spatula and bowl, with a consistent mixing time of less than 1 min. During the working time, the mixed cement was forced into a silicon mold until the mold cavities were completely filled. Cylindrical compression specimens with 6 mm diameter and 12 mm height (according to ASTM F451) were obtained (fig. 1).

After 30 min the test specimens were removed from the mold and kept for 24 h to ensure completion of the polymerization process. To obtain the final shape, all samples were polished with 600 grit abrasive paper until the surface was free of mold marks. A total of 54 cylinders were cast using this method.

Fig. 1. The cylindrical test samples

Specimens having surface damaged were excluded after visual inspection, leaving 34 samples for the test, which were soaked in PBS (phosphate buffered saline). It is recommended that specimens should continuously be maintained in the PBS solution from a minimum of 7 days to 60 days according to ASTM F 2118-03 (Standard test method for constant amplitude of force controlled fatigue testing of acrylic bone cement materials).

After being kept in saline solution for 7 days, the specimens were subject to a compression test on a 5kN Zwick/Roell traction-compression machine. Following the guidelines specified in ASTM F451 (Standard specification for acrylic bone cement), a test speed of 20 mm/min was used, while test conditions were room temperature (23°C) and 20% relative humidity.

Elastic modulus, Poisson's ratio and compressive strength were calculated. To determine Poisson's ratio, the test speed was set to 1 mm/min, according to ASTM E132-04 (Standard test method for Poisson's ratio at room temperature). Samsung SIR-4160 high speed camera and SigmaScan Pro image processing software were used in order to measure the transverse strain.

## Results and discussions

The load–longitudinal displacement curves of all bone cements samples tested exhibited similar linear elastic regime (load up to 2086 - 2502 N corresponding to 0.83 – 1.09 mm displacement), followed by yielding and a local maximum (2387 - 2843 N applied load, corresponding to 1.15 - 1.53 mm displacement). The curves presented in figures 3 and 4 were obtained by means of interpolation of the individual results.

The compressive strength values obtained exceeds the minimum value of 70 MPa specified in ASTM F451, as showed in figure 4. Test results show that the average compressive strength of the samples is 91.55 MPa (range: 84.63 – 100.54 MPa).

Using equation (1), the compression modulus was calculated for each sample. The average modulus for all the bone cement samples tested was determined to be 1483 MPa (range: 1025 – 1940 MPa).

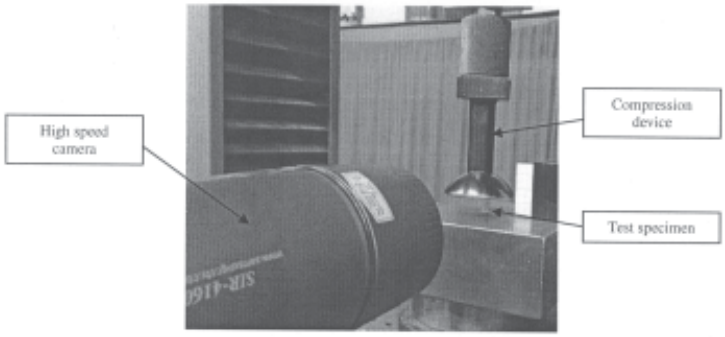


Fig. 2. The experimental compression apparatus

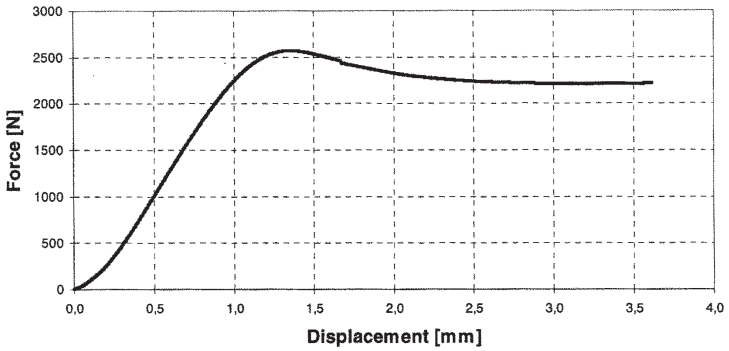


Fig. 3. Force – displacement curve

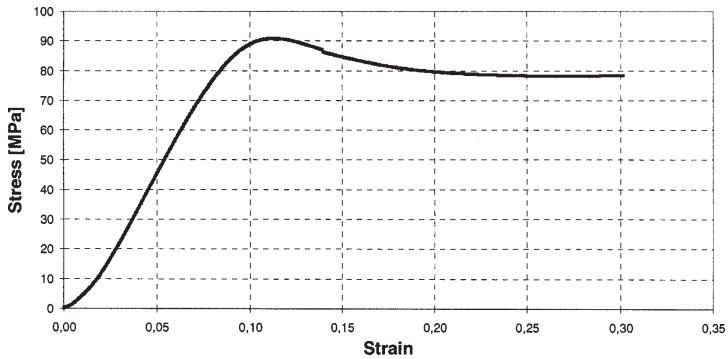


Fig. 4. Compressive strain-stress curve

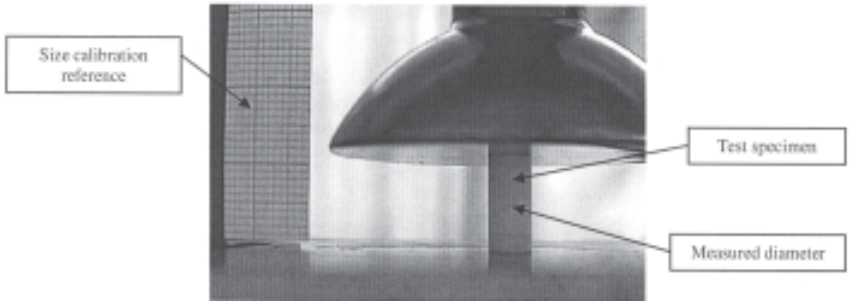


Fig. 5. Transversal strain measurement

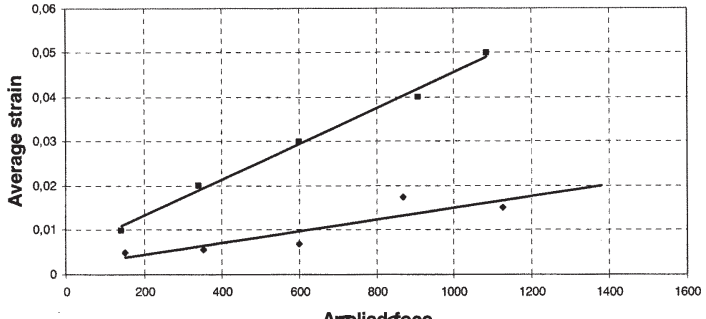


Fig. 6. Average strains versus applied force for Poisson's ration determination

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \quad (1)$$

In order to determine Poisson's ratio, the average longitudinal strain, $\varepsilon_l$, and the average traverse strain, $\varepsilon_t$, measured by the high speed camera and SigmaScan Pro image processing software (fig. 5.) were plotted against the applied force as shown in figure 6.

A linear trendline was drawn through each set of points and the slopes ($d\varepsilon_t$ / dP, $d\varepsilon_l$ / dP) of these lines were determined. Poisson' ration was calculated using the following equation:

$$\nu = \frac{\frac{d\varepsilon_t}{dP}}{\frac{d\varepsilon_l}{dP}} = 0.41 \quad (2),$$

where:

$d\varepsilon_t$ is the change in transverse strain,

$d\varepsilon_l$ is the change in longitudinal strain,

$dP$ is the change in applied load.

The obtained value for Poisson's ratio, marginally higher than the ratio of the bone, is justified because optimal transfer of loads between the bone and the prosthesis must be ensured.

## Conclusions

Compressive properties of Biomet® bone cement determined in our experiments can be compared favorably with previously published data. For example, the compressive strength for Simplex® bone cement is 97 MPa according to Kurtz and associates [3] and in the range between 84.8 - 114.3 MPa according to Lewis [21]. Therefore, the compressive properties measured for Biomet® are in agreement with published literature.

Additionally, the acrylic bone cement exhibits linear-elastic behaviour under compression, thus in FEA it can be modelled only using the modulus of elasticity and Poisson's ratio. It is recommended that in vivo stresses do not exceed the elasticity limit of the cement.

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