Requirements, modifications and methods of mechanical testing of bone cement – literature review

Wymagania, modyfikacje i metody badań mechanicznych cementu kostnego – przegląd literaturowy

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STRESZCZENIE

Artykuł ma na celu pokazanie podstawowych wymagań stawianych cementowi kostnemu, dotychczas stosowanych jego modyfikacji w aspekcie właściwości fizycznych, mechanicznych i biologicznych oraz podstawowe sposoby i metody jego badań. Owa pozycja ma stanowić źródło usystematyzowanej podstawowej wiedzy dotyczącej modyfikowanego cementu kostnego.

ABSTRACT

The Aim of the paper is to show the basic requirements for the bone cement, its modifications in terms of physical, mechanical and biological properties and testing methods. This publication is intended to be a source of systematized basic knowledge regarding the modified bone cement.

Słowa kluczowe: *cement kostny, badania mechaniczne, właściwości biomechaniczne, bioaktywność.*

Key words*: bone cement, mechanical test, biomechanical properties, bioactivity.*

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INTRODUCTION

Bone cement is a biomaterial used in medicine to fix implants, fill bone defects and stabilize fractures. It is a special self-polymerizing mass - obtained by mixing two components (Fig. 1): liquid and powder (i.e. a polymer with a monomer) and initiating the radical polymerization process. As a result, the bone cement obtains a porous structure composed of mutually tangled chains [1-3]. After the polymerization process and planting in the body, the bone cement mass is curing and fulfills a certain function. The bone cement powder has the form of regular beads or irregular particles of micrometric size. It contains the component initiating the polymerization reaction, while the inhibitor is contained in the liquid [3,4]. There are various types of bone cement, the most popular include: polymeric, phosphate-calcium, hydrogel, composite, bioactive acrylics [5,6].

Fig. 1. *Components of bone cement and instruments for its preparation*

REQUIREMENTS

The following characteristics are desired in the bone cement used in bone surgery [5-10]:

- the ability to properly transmit static and dynamic loads,
- biocompatibility,
- properties similar to bones (eg. elasticity),
- high fatigue strength,
- resistance to cracking,
- resistance to abrasive processes,
- wear resistance,
- high friction coefficient,

- relatively short bonding time,
- suitable polymerization temperature,
- high vibration damping factor.

If the appropriate properties are missing, the bone cement wears out too quickly loosening of an implant or insufficient fracture stabilization occurs. In more complicated cases, cracking of an implant or acute infection may occur. Other problems associated with the use of bone cement include: excessive temperature of polymerization process - which may cause thermal damage to surrounding bone tissue and extravasation; and also high polymerization contraction - which leads to improper anchoring of an implant [5-10].
In compliance with ISO 5833 standard the following minimum mechanical properties should be specified for the bone cement [11]:

- compressive strength $\geq$ 70 MPa,
- bending tensile strength $\geq$ 50 MPa,
- elasticity modulus $\geq$ 1800 MPa.

It should also be noted that the integrity of the bone-cement complex is a key aspect of its application, since the success of the implantation depends on the consistency of this combination. It was found that the boundary of this anastomosis is the most vulnerable to local lesions – which may later lead to its weakening and, as a result, various pathologies [12].

PROPERTIES OF THE BONE CEMENT

Table 1 presents the experimental values of the basic properties of the selected PMMA bone cements:

Table 1. *Sample values of the basic properties of the selected PMMA bone cements [4,12-15]:*

	Bone Cement (PMMA)					
Property	OSTEOBONG	CEMEX Isoplastic	PALACOS R	PALACOS R	PALACOS R+G	Bone Cement (The CMW Endurance)
Tensile strength [MPa]	40,49	----------	----------	----------	----------	----------
Compressive strength [MPa]	105,33	85,15	104,56	----------	85,9	----------
Flexural strenght [MPa]	----------	45,95	69,74	50,1	46,3/56,3	----------
Hardness [MPa]	----------	24,78	19,76	----------	----------	----------
Module E [GPa]	----------	----------	----------	2,81	1,8/2,2	----------
Hydration degree [%]	----------	----------	----------	----------	2,69	----------
Maximum polymerization temperature [°C]	----------	----------	----------	----------	----------	64
Contact angle [°]	----------	----------	----------	----------	----------	75,47

MODIFICATIONS OF PHYSICAL PROPERTIES

Additives that modify the polymerization temperature and curing time [10,12,16-18]

In order to reduce the polymerization temperature and accelerate the curing time the following modifications of the bone cement listed in the literature were investigated:

- nanoparticles of magnesium oxide,
- nanoparticles of hydroxyapatite,
- nanoparticles of chitosan,
- nanoparticles of barium sulfate,
- nanoparticles of silicon oxide,
- nanospheres and microspheres of PMMA,
- particles of MMA,
- particles of carboxymethylocellulose.

The use of these additives affects the temperature in a variety of ways. Some of them reduce the temperature – which is desirable, while others are neutral or even increase it. The same is true for curing times. The best results found in the literature were obtained after the addition of magnesium oxide with the concentration of 2 wt%, where the maximum temperature was about 11% lower than the temperature of the bone cement without modification (i.e. 58,9 °C). For the curing time, the best effects were obtained for hydroxyapatite with the concentration of 2 wt% (shortening by 2:05 min) and also for magnesium oxide with the concentration of 6 wt% (shortening by 2:50 min) [10]. In turn, the addition of carboxymethylocellulose reduced the curing time by approximately 40% (0,20 wt%) [18].

Additives used as contrasting agents

Typical additions allowing the visibility of bone cement in X-ray are the particles of: $BaSO_4$ (8-10 wt%) and ZrO_2 (10-15 wt%) [19,20]. Also, the particles of i.a.: Al_2O_3, SrO, SrHa i TiO_2 underwent the experimental testing [20-23].

MODIFICATIONS OF MECHANICAL PROPERTIES

In order to increase the basic mechanical properties of bone cement, the following additives were tested: [4,11-17,20-25,30]:

- carbon nanotubes,
- particles of polyethylene,
- titanium oxide fibers,
- nanoparticles of titanium oxide,
- nanoparticles of hydroxyapatite,
- nanoparticles of fluoroapatite,
- nanoparticles of silicon oxide,
- mesoporous nanoparticles of silica,
- fibers of polyethylene terephthalate,
- particles of ammonium nitrate,
- particles of montmorillonite,
- glass fibers/flakes,
- nanoparticles of ,,core-shell'',
- nanoparticles/nanotubes of zirconia.

For example, carbon nanotubes (diameter: 40-60 nm, length 0.5-40 nm) were added to the liquid bone cement component. The solution was then sonicated and the polymerization was initiated at 50°C. The addition of carbon nanotubes improved the tensile strength and compression strength of bone cement by approximately 20% [11]. The use of hydroxyapatite or fluoroapatite nanoparticles (diameter about 20 nm) also increased the strength properties of bone cement. In case of compression strength by 3,7 % (5 wt% HA), 12,3% (5 wt% FA) and 6,2% (8 wt% HA), 10,3% (8 wt% FA). Tensile strength increased by 16,7% (5 wt% HA), 36,7% (5 wt% FA) and 28,3% (8 wt% HA), 52% (8 wt% FA).These additives have also increased the hardness of the bone cement by 6% (8 wt% HA) and 27% (8 wt% FA) [27]. Another example of an additive that is beneficial for the mechanical properties of the bone cement are the nanoparticles or nanotubes of zirconium - whose usage increased the compressive strength of the bone cement by approximately 48% (20 wt%) [30].

The additive which was used does not always have beneficial effects in every respect – for example, MSN nanoparticles (5 wt%) increased compression strength of the bone cement by 4,2 % but also reduced bending strength by as much as 16% [4].

MODIFICATIONS OF BIOLOGICAL PROPERTIES

There are two main aspects of the modification of biological properties, i.e.: the effect on osteointegration and antimicrobial properties. Currently, a commercially used solution is the addition of antibiotics (e.g. gentamicin, tobramycin or clindamycine) [31-33]. Silver nanoparticles, hydroxyapatite particles or bioshell particles were also tested experimentally [34-36].

PHYSICAL TESTS

Test of polymerization temperature and curing time [10,26,41]

A four-channel thermocouple can be used to measure the temperature. It is connected via a DAQ to a computer. A specimen of the bone cement is placed on the table and pressed with the weight of 1.633 kg. Temperature changes are recorded every 25 seconds until bone cement hardens. This is assessed by striking the specimen with the steel needle. The lack of an imprint on the surface means that the curing process is completed. An exemplary temperature recorded in the literature is 64 °C.

Porosity test [26,37]

The evaluation of the porosity of the obtained bone cement can be assessed using microscopy, e.g. SEM (Fig. 2). It is also possible to calculate the total porosity using the dependence:

$$P(\%) = 100(1 - (db/dp)) \quad (1)$$

where:

db – volume density (M/V),
M – mass of the sample,
V – volume of the sample,
dp – density of the powder (as measured by gas pycnometry).

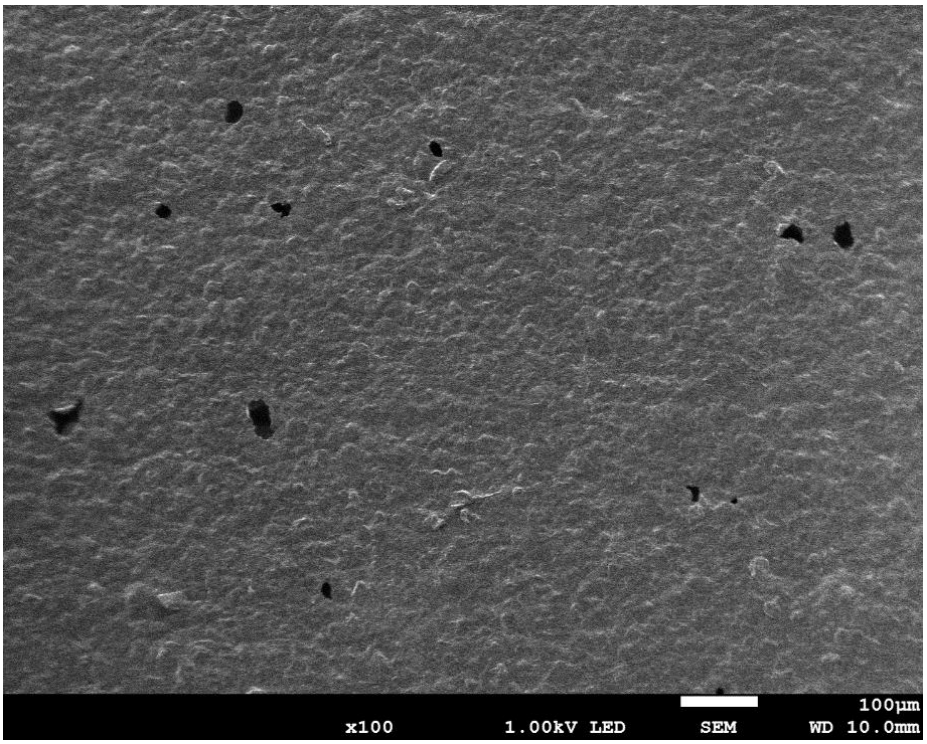

Fig. 2. *The topography of the surface of the bone cement sample*

Testing the distribution of modification particles [20,27,37]

For the evaluation of the particle distribution - it is possible to use microscope such as SEM or, in the case of contrasting agents, the elemental mapping technique using EDS X-ray spectroscopy.

Testing the hydration absorption [4]

The test consists in immersing the specimens in a distilled water solution and placing it at 37 °C for the period of 21 days (m_w). Then, the specimens are placed in a dryer at 50 °C for 24 h (m_f). At each stage of the test, the specimen should be weighed. Once the results have been obtained, two parameters can be identified from the fomulas, i.e. the hydration degree (H_a) and the degree of rinsing (E_w).

$$H_a\,(\%) = \left(\frac{m_w - m_f}{m_o}\right) x100 \tag{2}$$

$$E_w(\%) = \left(\frac{m_o - m_f}{m_o}\right) x100 \tag{3}$$

where:
m_w – mass of the wet sample,
m_f – mass of the sample after drying,
m_o – initial mass of the sample.

Evaluation of the degradation in an aggressive environment [14,28-30,40]

The test aims to reflect the impact of an aggressive environment (i.e. placing in the human body) on the specimen of bone cement (Fig. 3). Examples of solutions that are used as

the so-called SBF (simulated body fluid) are Ringer's fluid and Hank's fluid with an ionic composition similar to human blood plasma and Ph 7,4. The test involves placing the specimen in solution at 37 °C for 4 weeks. The structure of the bone cement is then analyzed using microscopy, e.g. SEM (Fig. 4)

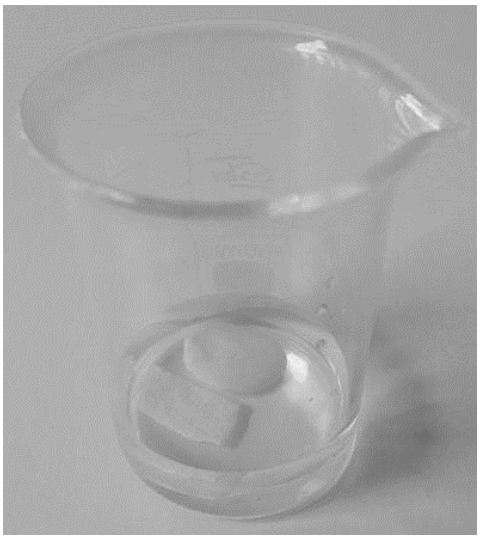

Fig. 3. *Sample of bone cement immersed of SBF solution*

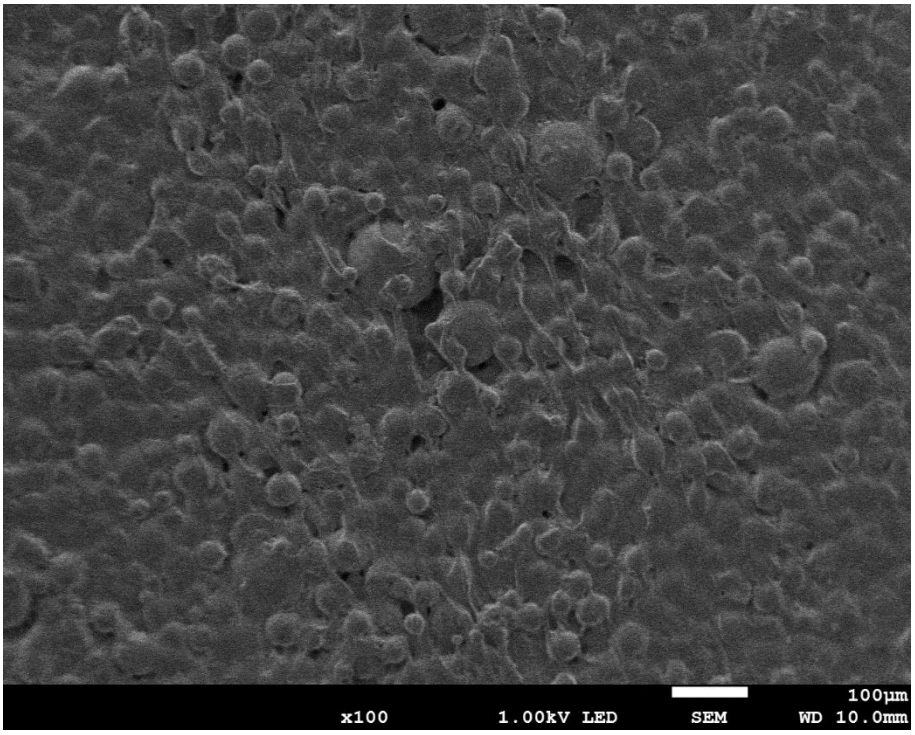

Fig. 4. *The topography of the surface of the bone cement after immersion and retention in SBF solution (24h)*

Testing the contact angle [39]

The test aims to determine the hydrophilicity of the bone cement surface. Distilled water and/or ethylene glycol are used to carry out the test. The drops are applied onto the specimens and the angle is measured using a goniometer or optical tensiometer (Fig. 5). One must remember that the sample surface is relatively flat, smooth and free from contamination.

Fig. 5. *Measurement of the contact angle the of bone cement specimen*

Testing the injectability [26,40]

The injectability test is carried out using an infusion pump and 10 ml syringe at an extrusion rate of 120 ml/h and the force of 88 N. The syringe tip is 2 mm in diameter and the syringe is filled with 8 g of bone cement slurry. To calculate the percentage value of this parameter the following dependence is used:

$$Injectability\ (\%) = \frac{mass\ extruded\ from\ the\ syringe}{total\ mass\ before\ injection}\ x\ 100\% \qquad (4)$$

MECHANICAL TESTS

Preparation of samples [1-4]

Bone cement is prepared in two main ways: manually or using vacuum. In the case of manual mixing, the bone cement ingredients are combined and mixed for at least 60 seconds. In the second case vacuum mixing device is used. Suitable, specially prepared moulds are used to prepare the appropriate specimens of the intended shape (usually beam) and dimensions. The simplest way is to place the bone cement slurry in the moulds manually, using a dedicated spatula. Various types of forms are available: steel, PTFE or Teflon. Samples should „rest" in the form for at least 15 min. After removing the specimens from the moulds, their quality should be assessed and appropriate specimens for test can be selected. In the case of planning surface test, the surface of the specimen should be ground and polished.

In compliance with ISO 527 and ASTM F2118 standards defining the strength tests procedure, the test specimens - have standardized shape and specific dimensions [42,43].

Tensile and compression strength

Endurance tests are carried out on endurance machine with 2N preload and the displacement value of 0.5-5 mm/min. Endurance tests are usually carried out until 80% of the maximum destructive force is achieved [1,27]

More accurate results are obtained for tests conducted in an environment similar to the human body. An example of such a procedure is the use of continuous flow of saline solution at 37 °C [4]. Another possibility is to perform endurance tests for the bone-cement complex [13].

Combining the of endurance tests with sound emission testing seems to be a good solution, since it allows for more accurate detection of crack initiation moment and its propagation [44].

Fatigue strength

Fatigue strength tests are carried out with cyclic loading of the samples until they are destroyed. Sample parameters of the test are: 5 Hz and variable force: 100 N and 10 N [14] or 3 Hz and variable force ±20 N [44]. This test aims at determining the maximum number of stress cycles that do not damage the specimen. The test is carried out until the specimen breaks or until a specimen number of cycles is reached. As with other mechanical tests, they can be carried out under elevated temperature and Ringer's solution. The fatigue fracture cracks can be then analyzed by means of microscopy, e.g. SEM [44].

Flexural strength

An exemplary bending strength test is a three-point bending test with the pressure ratio of 1 mm/min. The test is carried out on a tensing machine until the specimen is destroyed [3,16]. The following dependencies are used to determine the flexural strength σ_t and Young's modulus E [3]:

$$\sigma_t = \frac{3PL}{2wh^2} \tag{5}$$

where:
P – maximum load,
L – specimen length
w – specimen width,
h – specimen height.

$$E_f = \frac{\Delta PL^2}{4wh^3 d} \tag{6}$$

where:
P – applied force range,
L – specimen length,
w – specimen width,
h – specimen height,
d – adequate deviation for a given range of forces.

Another possibility consists in carrying out the test of the four-flex bend. Exemplary parameters are follows: 250 N load, 5 mm/min pressure, 100 Hz [15,47]. Based on this test, it is also possible to determine the E modulus and the bending stress using the dependence [46]:

$$E = \frac{a(3Lx - 3x^2 - a^2)}{12I} \frac{\Delta F}{\Delta d} \tag{7}$$

where:
a – distance between the inner support,
L – distance between the external support,
x – the position in which the deflection is measured,
I – torque of the cross-section inertia
ΔF/Δd – inclination of the linear part of the displacement curve.

$$\sigma_F = \frac{3Fa}{bh^2} \tag{8}$$

where:
a – distance between the inner support,
F– applied load at break,
b – specimen width,
h – specimen thickness.

Hardness test

Microhardness measurements can be performer using the Vickers method with a diamond probe. Exemplary test parameters are: load 50 g and dwell time 15 s or load 200 and dwell time 10 s. A more accurate version of the test reflecting the operating environment of the bone cement involves immersing the specimen in Ringer's solution at 37 °C [27,49]. The following dependence is used to determine the hardness:

$$H = (1{,}854 \cdot \frac{F}{d^2}) \cdot 9{,}807 \tag{9}$$

where:
F – applied force,
d – average diagonal of the impression.

It is also possible to nother possibility to carry out the hardness test using a nanoindenter and performing the so called scratch test. Sample parameters of nanohardness testing are: load 450 mN, load gain 15 mN/s, dwell time 15 s and for nanoscratch test: load 500 mN, scratch speed 0,13 mN/s, length of scratch 4 μm and scratch depth 300 nm [2]. Based on these tests, the hardness can be determined by the dependencies [48,50]:

For hardness test on the nanoindenter:

$$Hn = \frac{Fn}{A} \tag{10}$$

where,
Fn – maximum setpoint load,
A – area of contact between the specimen and the probe.

For the scratch test:

$$Hs = 2{,}31\frac{Fn}{d^2} \tag{11}$$

where,
Fn – maximum setpoint load,
d – the length of the scratch.

Abrasion resistance

The abrasion resistance test is carried out on a tribometer. Sample parameters of the test are: 6 mm steel ball, applied load 15 N, programmed track 1000 m and frequency 120 rpm. A specimen of bone cement for surface testing is immersed in saline solution and mounted on the device. The test consisting in moving the steel ball on the surface of the specimen along the prescribed path is then carried out. The following parameters: track depth and track

diameter should be considered. The test allows the determination of abrasion resistance and coefficient of friction [16,51].

BIOLOGICAL TESTS

Several basic biological tests can be disinguished: bacterial, cytotoxicity, cell adhesion and proliferation and clinical trials. The most basic test is the examination of the bacterial growth inhibition zone. The examination is carried out by placing a specimen of the bone cement in a bacterial growth medium (e.g. Staphylococcus aureus) after 24 h incubation with an initial concentration of bacteria of about 1-2x108 units/ml. Then, the range of retained bacterial growth is observed and measured [38,52,53].

CONCLUSIONS

1. The research on the bone cement modification is still ongoing. The most common aspects of applied modifications are: reduction of polymerization temperature, acceleration of the curing time, increase of the basic mechanical properties, improvement of the biocompatibility, providing the bioactivity of the bone cement in terms of bactericidity.
2. Testing of the bone cement requires a number of interdisciplinary tests, including: evaluation of the basic structure and porosity, polymerization temperature test, curing time test, compressive strength test, bending strength test, hardness test, testing of impact of aggressive environment and test of bacteria growth inhibitory zone.
3. In compliance with the standard requirements, the bone cement needs to have the compressive strength exceeding 70 MPa, the bending strength exceeding 50 MPa and the Young's modulus exceeding 1800 MPa.
4. Optimally functional bone cement that can be used in medicine is a combination of many features. First and foremost it should posses - high mechanical properties that are close to bone, however, it must be biocompatible at the same time. Current modifications are intended to provide the biofunctionality of the bone cement in order to enable and even stimulate the osteointegration and bioactivity, in terms of antibacterial properties.
5. Modification which improves one property can worsen another. Hence, testing the modified bone cement requires complex interdisciplinary research – in terms of its physical characteristics, mechanical, and biological properties. Detailed clinical trials should also be recommended.

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