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Determination of mechanical properties of impacted human morsellized cancellous allografts for revision joint arthroplasty

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This paper deals with the characterization of mechanical properties of impacted morsellized cancellous allograft (IMCA) produced by dynamic compaction of allograft femoral heads ground by commercially available bone mills, i.e. rotating rasp and reciprocating type bone mills. Various ranges and profiles of particle size in the graft aggregates were obtained using these bone mills, and the effect of number of compaction as well as the distribution of particle sizes on the mechanical properties of IMCA under quasistatic compression and shear loading conditions was discussed. The morsellized cancellous allograft prepared by the reciprocating type bone mill showed a broad distribution of particle sizes, and gave IMCA superior mechanical properties to the graft with a more uniform size distribution, or prepared by the rotating rasp type bone mills. The increase of number of compaction also improved the mechanical properties of IMCA in compression.

1. Introduction

Revision total hip arthroplasty with massive femoral intramedullary bone loss is a challenge to surgical reconstruction. A technique using impacted morsellized cancellous allograft (IMCA) has been developed for such deficient bone stock cases and some encouraging early results have been clinically reported [1–3]. However, large early subsidence of the femoral stems, probably due to poor mechanical properties of IMCA, has also been reported [4]. In some recent studies IMCA was considered to be particulate aggregates, and its mechanical behavior was characterized with an application of engineering soil mechanics [5, 6]. Thus, preparation of the morsellized allograft could be one of the key factors to the success of revision surgery, but few studies on its optimum preparation have been performed so far. Hence, this paper deals with the determination of the mechanical properties of several IMCA containing different ranges and profiles of particle size, and the objectives of this study can be explicitly stated as:

1. To determine the range and profile of particle sizes in graft aggregates, or IMCA produced by dynamically compacting allograft femoral heads ground by currently available bone mills.
2. To determine the mechanical properties of IMCA under quasistatic compression and shear with respect to the range and profile of particle sizes, and the number of dynamic compaction.

2. Materials and methods

2.1. Preparation of morsellized cancellous allograft

Human femoral heads were obtained from patients with femoral neck fracture or osteoarthritis during total hip arthroplasties. Femoral heads were stored at $-70\,^{\circ}\mathrm{C}$ until testing. After removing soft tissue and cartilage, femoral heads were equally cut into four pieces and divided into four groups at random to minimize heterogeneity among femoral heads.

Two types of bone mills, namely, a rotating rasp type (Tracer Designs, Zimmer, Santa Paula, CA, USA) and a reciprocating blade type (Lere Bone Mill, DePuy IN, USA), were used for graft preparation. Three kinds of rasps (designated fine, medium and coarse) were used in the rotating rasp type. Morsellized bone was prepared using these four different bone mills (Fig. 1).

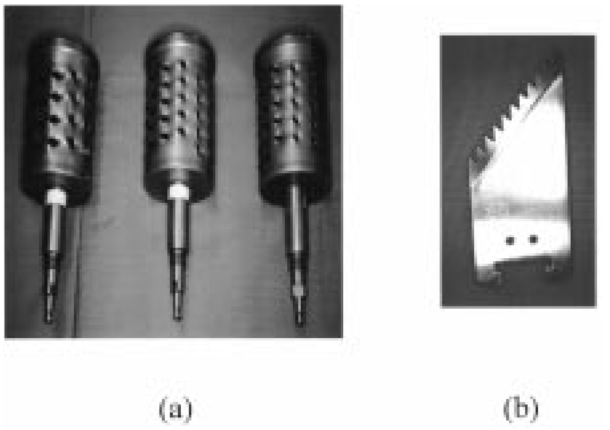

Figure 1 Appearances of rotating rasps and blade of bone mills used in this study: (a) three kinds of rasps (coarse, medium and fine from left to right); (b) a reciprocating blade.

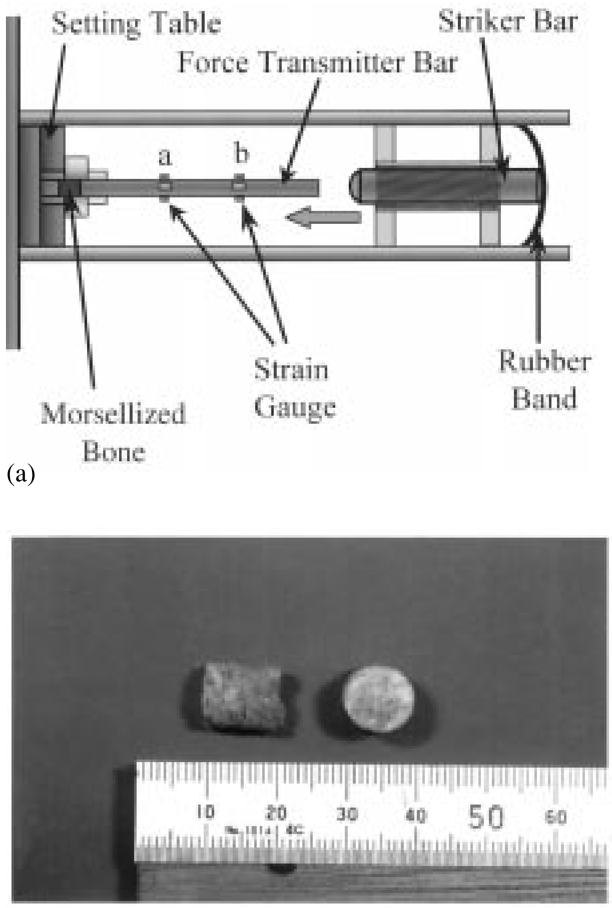

Figure 2 (a) Dynamic compaction apparatus and (b) cylindrical IMCA specimen produced.

2.2. Particle size determination

The distribution of fragment sizes of morsellized bone for each bone mill was calculated. To this end, a part of IMCA specimens after 30 times compaction, as described in section 2.3, was washed in ethanol, and then dried. Seven specially designed sieves, i.e. plastic plates with drilled holes of diameter in a range of 2 to 8 mm at every 1 mm were made to determine the size of the fragments. The sieves were used in order of decreasing hole diameter with the largest at the first. Approximately 500 mg of morsellized bone taken from one IMCA specimen were firstly placed on the sieve with the largest holes and then the sieve was manually shaken until no further passage of fragments down the gradient occurred. The same procedure was applied to the other sieves. The number of particles remaining in each sieve was counted, and the percentage of the graft in each sieve was calculated. That is, the number distribution of particles in the sieves was used to represent the distribution of particle sizes in this study.

2.3. Production of IMCA specimens by dynamic compaction

Cylindrical IMCA specimens 10 mm in diameter and 10 mm in length were made by a specially designed dynamic compaction apparatus (Fig. 2). The apparatus consists of a striker bar, a force transmitter bar, a setting table and recording equipment. Given quantities of the morsellized bone were filled in the hole in the setting table and the force transmitter bar was placed on it. An impingement of the striker bar on the upper end of the force transmitter bar generates compressive stress pulse travelling down the force transmitter bar, and eventually, the morsellized bone was dynamically loaded because of this stress pulse. Based on the one-dimensional wave propagation theory the impact force (F_c) applied to the upper end of the bone at any time (t) can be evaluated by the following equation [7]

$$F_c = A[\sigma_a(t + t_l) + \sigma_a(t - t_l) - \sigma_b(t)] \qquad (1)$$

where σ_a, σ_b = stress histories detected by strain gauges at the point a and b, respectively; A = cross-sectional area of the force transmitter bar; t_l = time required for stress wave propagation from point a to b or from point b to a.

The magnitude of an impact force was chosen to be the same as observed in another series of experiments on simulated femoral impaction grafting [8], and controlled to be approximately 4.2 kN on the average in this study. The impact force was applied to the bone 15 or 30 times to investigate the effect of the number of compaction on the mechanical properties of IMCA.

2.4. Mechanical testing

Quasistatic uniaxial compression tests as well as quasistatic shear tests at various normal compression loads were performed using an Instron type materials testing machine (Autograph AG-25TD, Shimadzu Co. Ltd, Japan). The IMCA specimens were tested without lateral constraint in the compression tests. Alternative shear testing apparatus to commercial apparatus used in the previous study [6] was purposely built for this study (Fig. 3). The IMCA specimen was put into a cylindrical plastic container with an applied normal load of 9.8, 19.6 or 29.4 N by a spring and then sheared by moving the cross-head downward at a constant speed. All mechanical tests were performed at a cross-head speed of

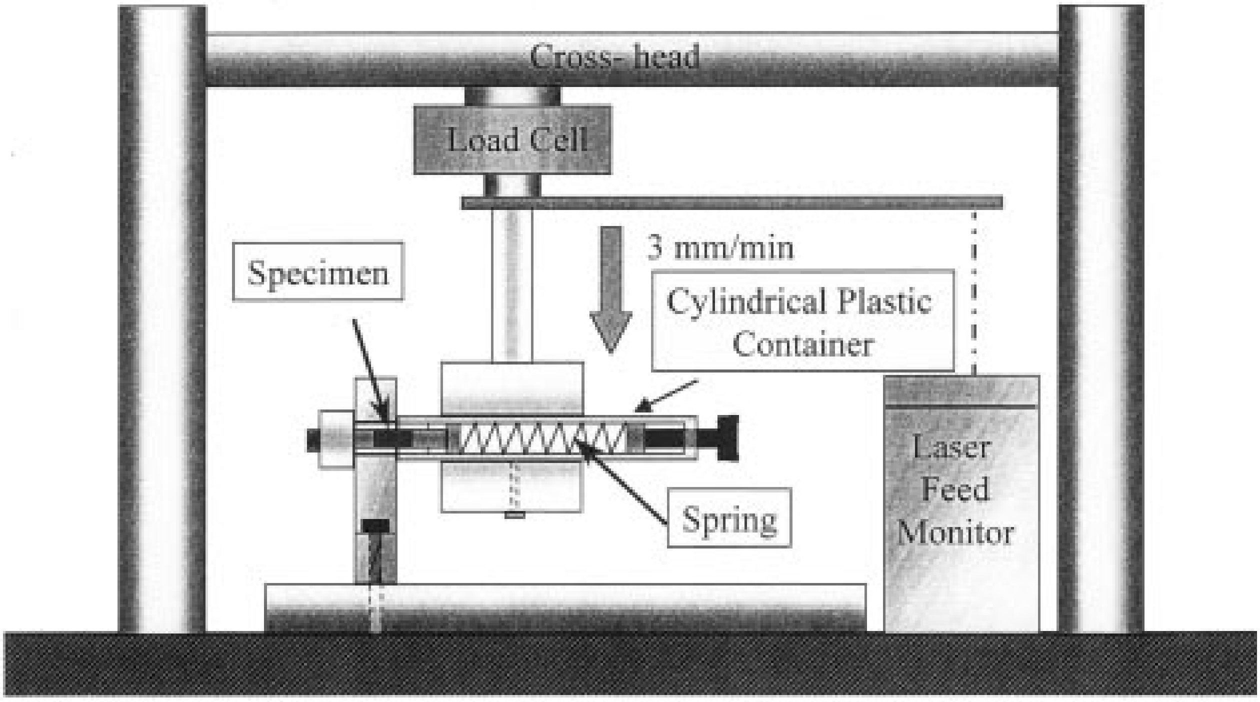

Figure 3 Experimental set-up for quasistatic shear tests on IMCA specimens. Tests with an application of normal load of 9.8, 19.6 or 29.4 N by a spring to the specimens were performed at a cross-head speed of $3\,mm\,min^{-1}$.

$3\,mm\,min^{-1}$ and at room temperature (20 °C). All specimens were kept moist during testing. Ten specimens were used for each test, and the results were statistically compared in four groups of IMCA produced by the four different bone mills.

3. Results and discussion

3.1. Particle sizes in morsellized bone

Fig. 4 shows physical appearances of bone fragments in each graft group. The fragments prepared by rotating rasps (fine, medium and coarse groups) were thin and

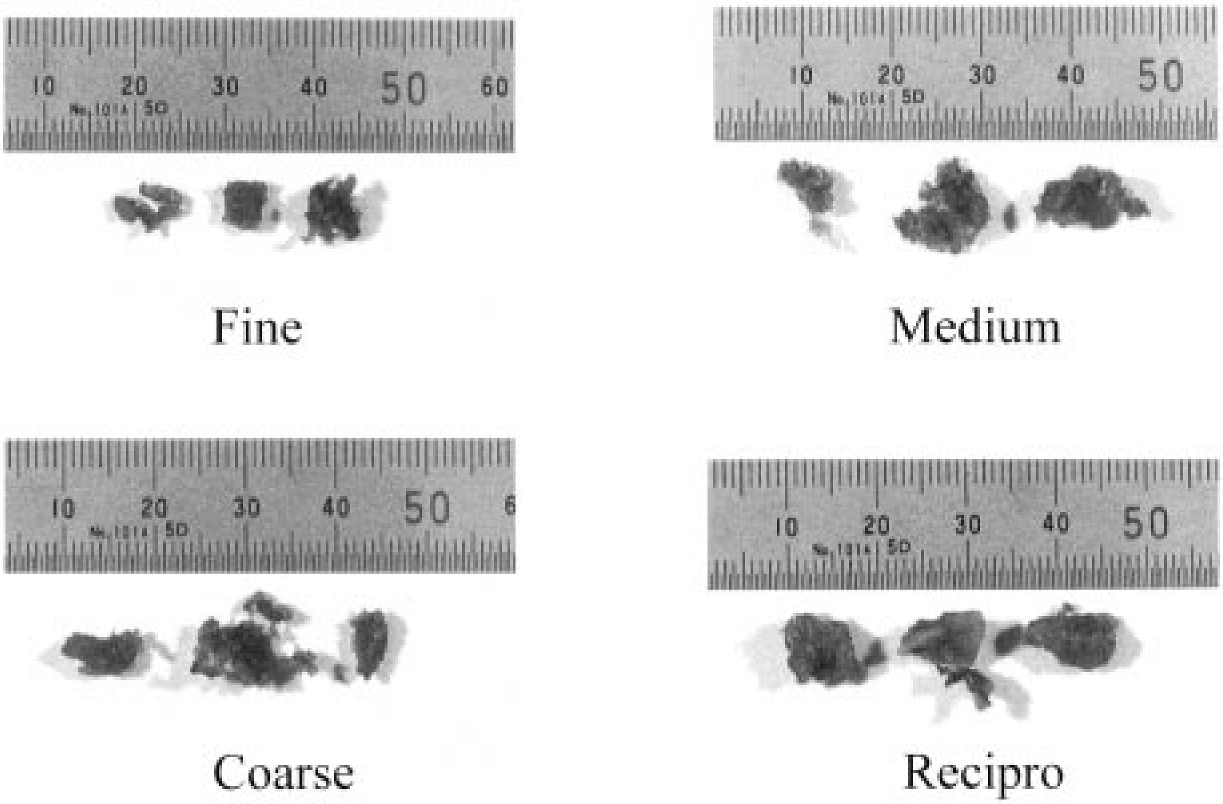

Figure 4 Physical appearances of morsellized bone fragments, as prepared with four different bone mills.

slightly curled while irregular shapes were observed in the fragments prepared by the reciprocating blade (recipro group). Distribution of particle sizes in each group was obtained as shown in Fig. 5. Morsellized bone prepared by the reciprocating blade contained larger bone fragments than those prepared by the rotating rasps, and clearly showed a broad size distribution as well.

3.2. Stress–strain behavior of IMCA under compression

Non-linear or downward convex characteristics were found in nominal compressive stress–strain curves of all IMCA specimens independent of the number of compaction. Stiffness in compression defined by the tangent modulus at strain of 0.2 on the stress–strain curve was evaluated and obtained for each graft group (Fig. 6).

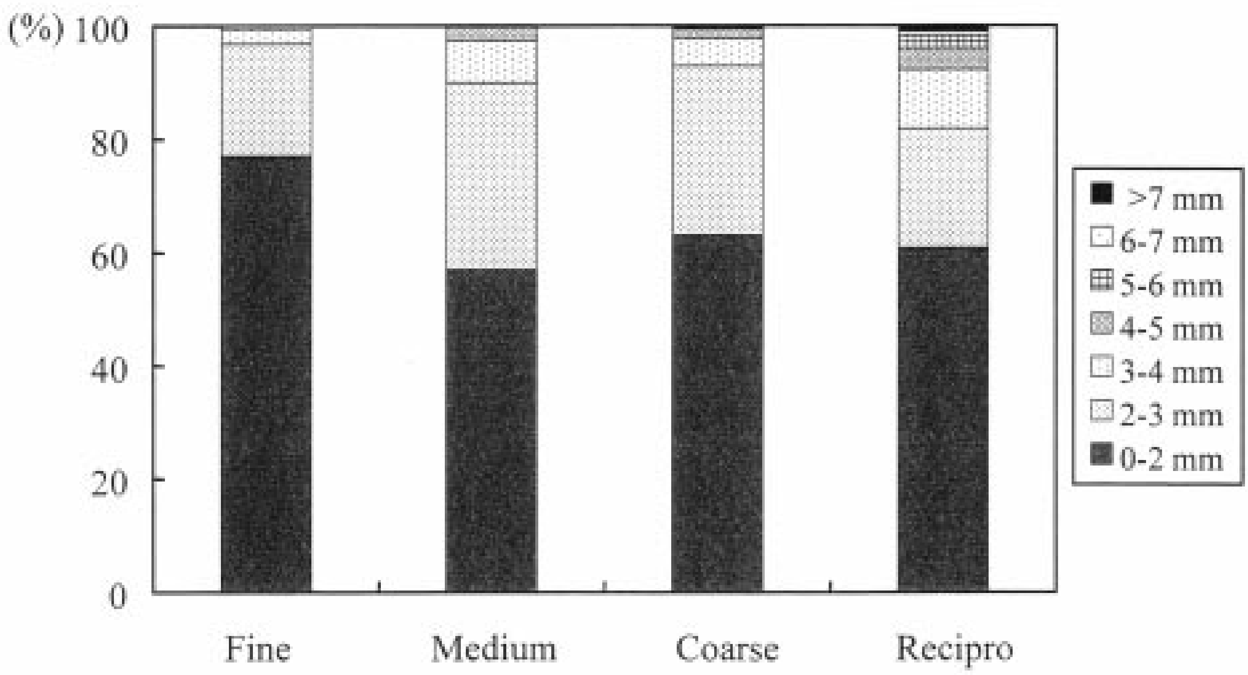

Figure 5 Percentage number distribution of particles for different bone mills.

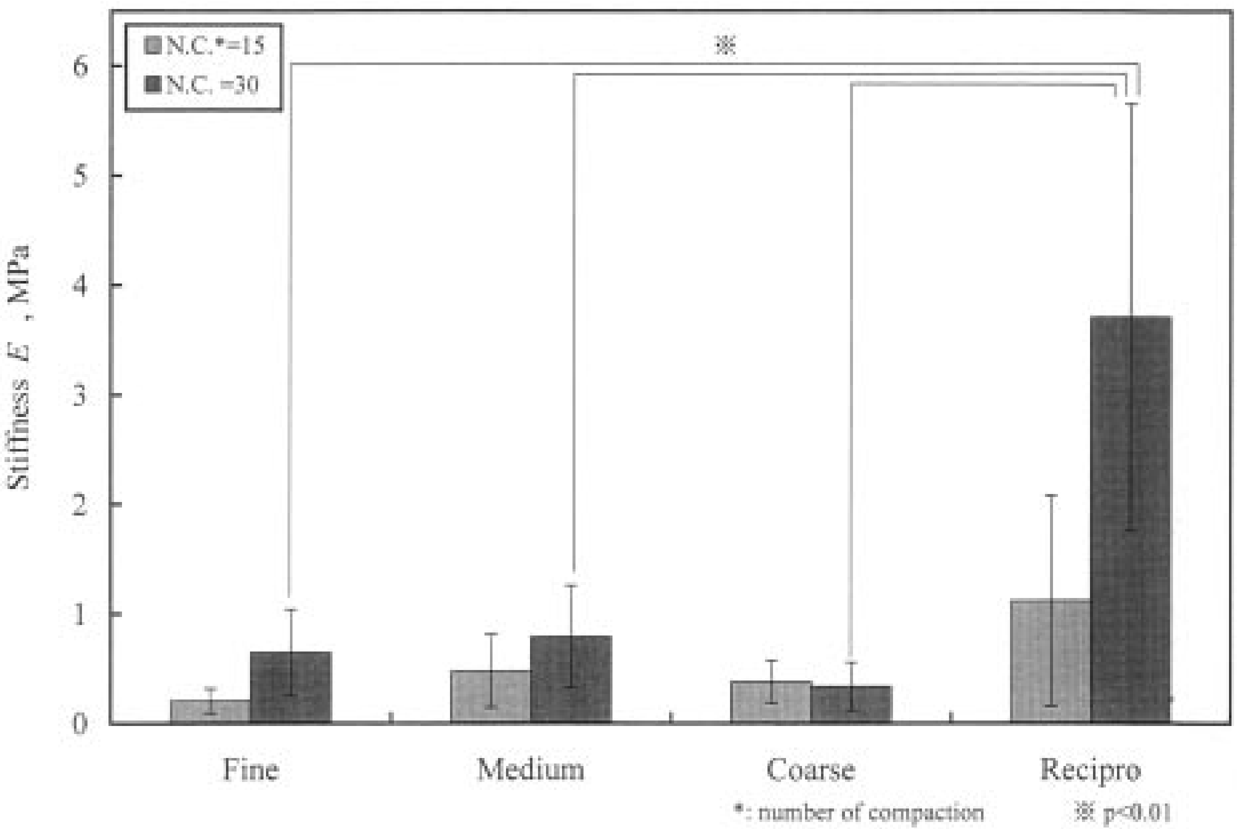

Figure 6 Stiffness of IMCA in quasistatic compression for each graft group. Stiffness was evaluated at strain of 0.2 on nominal stress–strain curve.*p<0.01.

The stiffness appeared to increase with increasing number of compaction in each group. In the case of 30 times compaction, IMCA prepared by the reciprocating blade showed significantly higher stiffness than that prepared by any other rotating rasp.

3.3. Mechanical strength of IMCA under shear

Load–displacement curves of all IMCA specimens under quasistatic shear obtained in this study were upward convex. Shear strength, defined as the maximum shear stress on the curve, was determined as a function of axial compressive or normal stress (Fig. 7). Since no effect of the number of compaction on the relationship between shear strength and normal stress in each graft group was found, only the result for the number of compaction of 30 was shown in this study. The result of Fig. 7 can be formulated by the Mohr–Coulomb equation [9] given as

$$\tau_u = c + \sigma_c \tan \phi \qquad (2)$$

where τ_u = shear strength, σ_c = normal stress applied, c = cohesive force, ϕ = angle of shearing resistance or angle of internal friction.

The shear strength parameters, c, ϕ and τ_u of each group are listed in Table I. IMCA prepared by the reciprocating blade showed significantly higher shear strength than that prepared by any other rotating rasp.

The results of Figs 6 and 7 indicate that the mechanical properties of IMCA were affected by the preparation method of morsellized bone and the number of compaction. The size distribution and the shape of bone particles were different among the four bone mills used in this study. It was not confirmed which factor mainly influenced the mechanical properties of IMCA, but morsellized allograft containing larger bone particles and/or broader particle size distribution seemed to bring superior mechanical properties to IMCA. Recently, some studies measured the implant stability *in vitro* using human cadaver femora, and IMCA with a cemented collarless polished tapered stem was reported to provide initial stability of the stem [10, 11]. This study has revealed that IMCA prepared by the reciprocating blade shows high stiffness and shear strength, and therefore could result in better success of the practical impaction femoral grafting. The mechanical initial stability of the femoral stem in revision arthroplasty using IMCA should be further discussed.

4. Conclusions

The broader range of particle size distribution in morsellized bone could contribute to the stronger

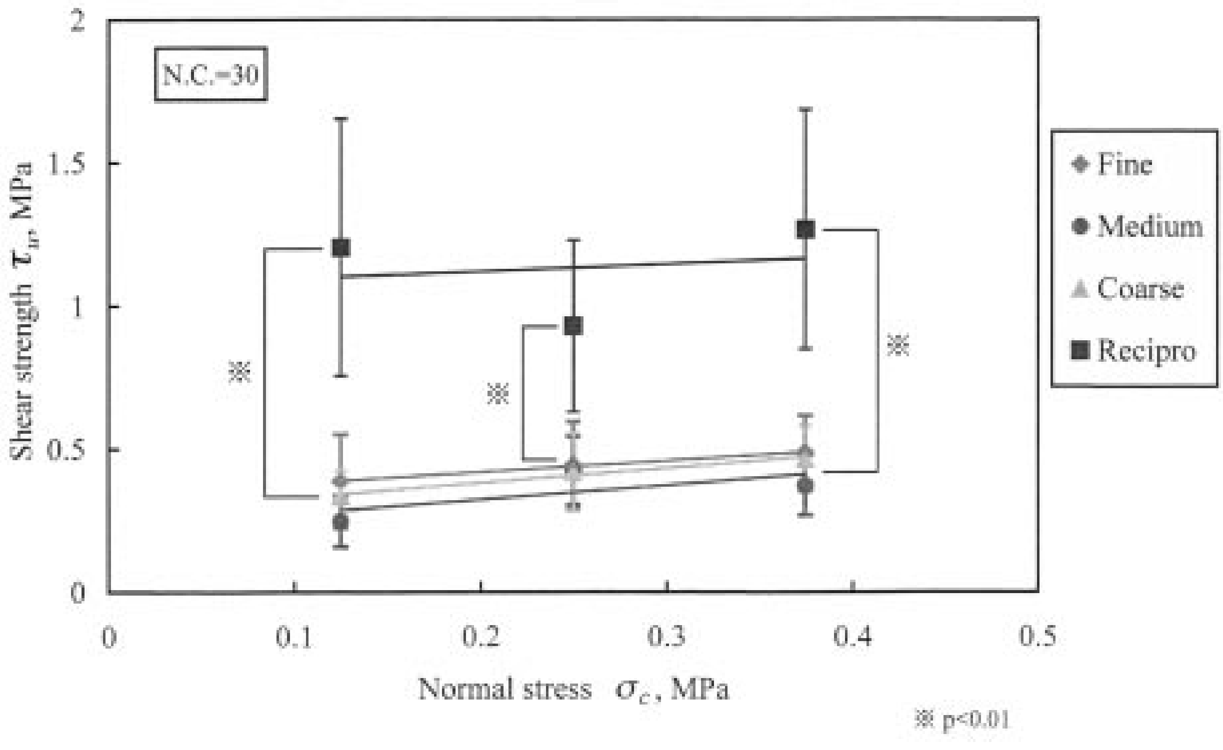

Figure 7 Shear strength of IMCA plotted against normal compressive stress. * $P < 0.01$.

TABLE I Shear strength parameters in Equation 2 for IMCA specimens compacted 30 times in each graft group

Group	Cohesion, c (MPa)	Angle of internal friction, ϕ (rad)	Average shear strength, τ_u (0.37 MPa normal stress) (MPa)
Fine	0.34	0.38	0.49
Medium	0.22	0.46	0.37
Coarse	0.28	0.48	0.46
Recipro	1.07	0.25	1.27

mechanical properties of IMCA. Thus, it is important for revision surgery to select the proper bone mill to obtain good initial stability.

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