5 SHEAR TEST

5.1 Experimental methods

When a patient loads his impaction grafted hip post-operatively the bone grafts are loaded in compression and shear so that an analysis of the shearing resistance of bone grafts seems essential to analyse the mechanical stability potential of grafts considered for impaction grafting. A shear-box adapted from the standardised soil mechanics uni-directional shear test[222] was employed to measure basic shear properties like shear angle, cohesion and dilation. These properties represent the shear resistance and they can affect mechanical stability against subsidence in impaction grafting, the compaction and the handling properties.

The geometry, mechanical principles and mode of operation of the shear box apparatus can be seen in figure 5.1. The specimen is confined in a metal box with a quadratic cross-section horizontally split in two parts at mid-height. Here, by design, the plane of shear failure is positioned. Porous plates with a toothed profile are placed at the bottom of the shear box and on top of the specimen to achieve proper load transfer into the granular material and to allow low resistance drainage of liquid. Alternatively, like in the experiments described here, solid metal plates can be used in addition to stop drainage and mimic the confined situation of a graft around an impaction grafted hip prosthesis. A vertical force causing normal stress in the pre-defined shear plane is applied to the specimen via a loading plate on top of the shear box which is pushed down by a weight plus load frame and lever system. Shear stress is quasi-statically applied via a horizontally moving screw driven by an electric motor pushing the lower half of the shear box against the top one. The resulting shear forces are measured by recording the deformation of a calibrated ring spring providing the reaction force for the upper half of the shear box.

During shear box operation, shear force, shear displacement and dilation, the changes in sample height must be recorded in 10-30s intervals for data analysis. Volume changes of particulate aggregates during shearing, called dilation are characteristic of a material's shear behaviour and can be indicative of certain stages of a shear experiment. Loosely packed particulate aggregates with low cohesion tend to show a volume reduction during shearing but can exhibit sudden increase in volume again when the material has asymptotically reached its ultimate shear resistance. Dense and cohesive materials under shear tend to behave in the opposite manner. Particles ride over each other and push themselves up under shear resulting in positive dilation. A sudden and steep volume increase can indicate that the material has reached its peak shear resistance. Shearing dense and cohesive materials further results in an asymptotic drop in shear reaction force to a value called the residual or gliding shear resistance. A shear test as described above must be repeated at least two or three times with varied normal stresses to gain data points for linear extrapolation of the Mohr-Coulomb failure envelope which delivers the two characteristic shear resistance values cohesion c and shear angle φ.

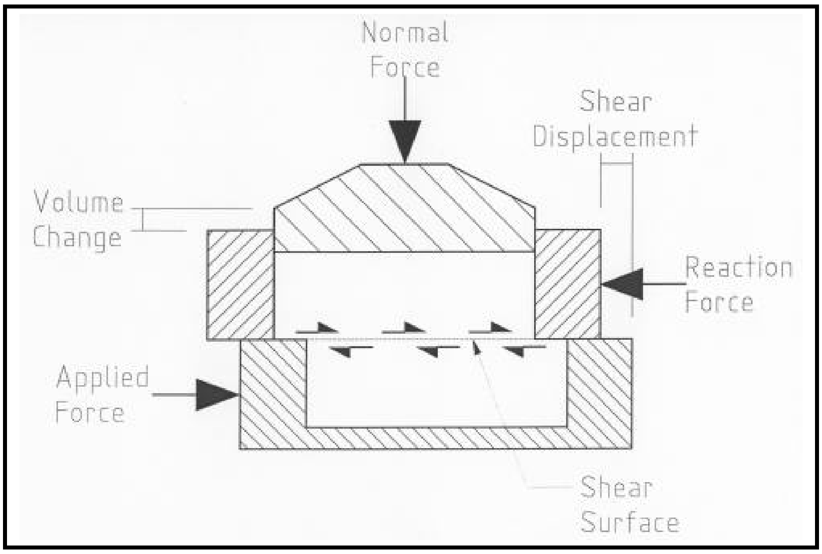

Figure 5.1: *CAD-drawing of shear box principle.*

In this study a standard civil engineering shear-shear box was used with the minimum square cross-section of 60 mm × 60 mm available to save bone graft material. The total height was reduced by washer plates to h_S= 50 mm in order to further reduce graft quantities consumed without sacrificing accuracy by interfering with the load transfer into the shear plane. As a result a minimum graft volume of 180 cm^3 was required per experiment. As grafts were condensed by the static normal loading the actual graft volume consumed per data point measured was even higher. Conducting a minimum of three such tests per graft configuration thus led to a high graft consumption of ca. 800cm^3. The shear box was modified with new mechanical dial gauges of higher resolution and less stiction than the original hardware designed for large volumes of crude soils instead of more sensitive bone grafts. The new instrument holders allowed a more accurate alignment of the metal parts and the gauges. Figure 5.2 shows a photo of the working apparatus where all parts, apart from the weight and lever, can be identified.

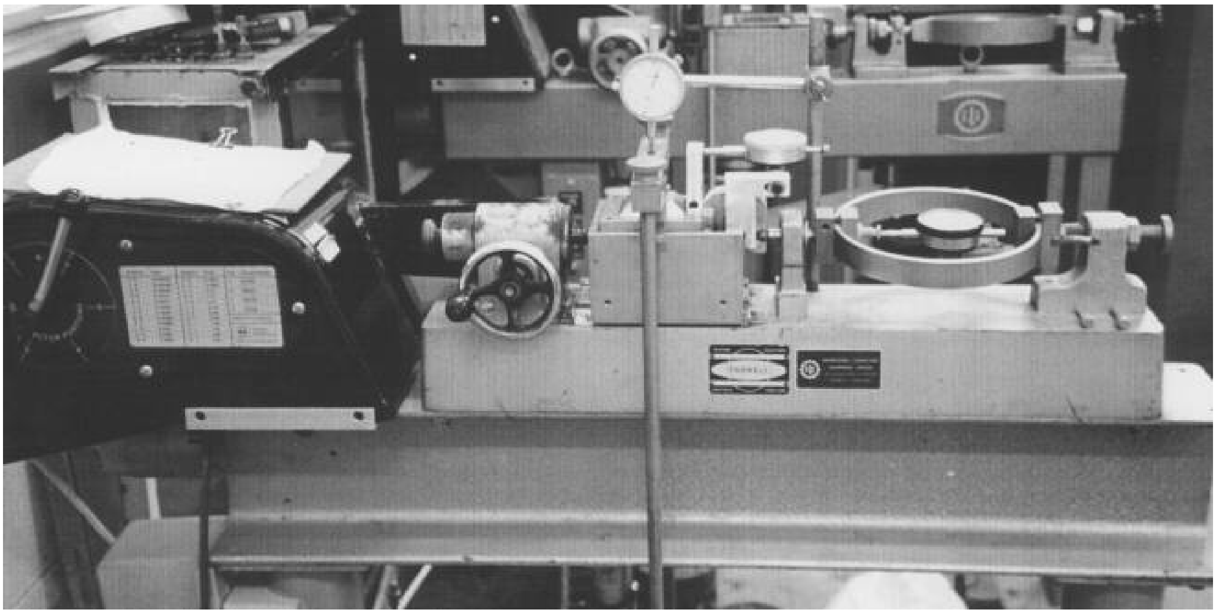

Figure 5.2: *Photograph of working shear box apparatus with the components from left to right: Motor, screw, shear box, loading frame for normal stress and ring spring. The three dial gauges from left to right record dilation, shear displacement and ring deformation.*

The experimental procedure is summarised in the style of an operating instruction below. A more comprehensive and exact description of all operational steps can be found in the civil engineering standards[222]:

1. Sample preparation by milling bone, sieving graft and mixing both components.
2. Filling shear box with no-drainage washer (optional), distance plate (optional), toothed plate, graft mix, toothed plate, distance plate (optional), no-drainage washer (optional), top plate.
3. Setting up load frame for normal load: Balancing frame on top plate with contact ball, applying static weight with lever system, adjusting clinometer into horizontal position.
4. Contacting shear box with screw
5. Adjusting and calibrating all three dial gauges into accurate positions. Recording start value.
6. Engaging motor gear and recording all three dial gauges simultaneously every 10-30s depending on the the steepness of the stress-strain gradient (beginning and end of experiment).

Below, a summary of experimental parameters applied during the shear-box test is given:

Shear box volume $b \times w \times h$:	60mm × 60mm × 50mm
Shear rate:	v_{shear}= 1 mm/min
Normal stress:	σ_N =61.7 kPa, σ_N =75.3 kPa, σ_N =88.9 kPa
Data acquisition frequency:	1 reading every 10-30s (shear and ring displacement, dilation)

5.2 Materials

The materials investigated in the shear box experiments were formalin fixed ovine bone graft morsellised with the Norwich mill and different mixtures thereof with the standard 80:20 HA/TCP synthetic bone graft substitute of medium (2mm< d <4mm) particle size and sintered at T_{Sint}= 1150°C with a 25% porosity. Shear properties of pure ovine bone, pure ceramic graft and two volume mixes with a 1:1 bone/ceramic and 1:9 bone/ceramic ratio were analysed. Due to the high graft consumption associated with the shear-box experiments, cohesion c and shear angle φ were only measured for pure ovine bone and both graft mixes. As the 1:9 bone/ceramic mix represents an extreme combination with a dominant ceramic fraction, cohesion and shear angle measurements for the pure ceramic were neglected. However, for one normal load, the stress-strain curve and the dilation-strain curve of a pure ceramic was recorded for comparsion. A summary of the materials tested follows:

- Pure ovine bone
- Pure 80:20 HA/TCP ceramic, 25% porosity, T_{Sint}= 1150°C, 2-4mm particle size,
- 1:1 bone/ceramic mix
- 1:9 bone/ceramic mix
- pure ceramic (one test)

5.3 Results

Cohesion and shear angle, as the two definitive characteristics of granular aggregates, describing the their shear properties, are derived from a set of at least three shear stress versus shear deformation diagrams as displayed in figure 5.3. It represents the stress-strain curves measured during a shear box test with the medium value normal stress of σ_N= 75.3 kN for pure bone, pure HA/TCP ceramic and two mixes thereof containing 50% (1:1 bone/ceramic) or 10% (1:9 bone/ceramic) bone. Qualitatively, all graft materials showed a similar correlation between shear stress and shear strain. The curves rose steeply first before gradients decreased and a maximum shear stress values were approached asymptotically, a behaviour which for soils often indicates a loosely packed material such as coarse sand[206, 220]. Other soils which are more cohesive or soils with saturated water form a clear shear stress peak before the stress-deformation curve drops slightly to a horizontal plateau of constant stress gliding. The maximum strains before shear failure were at approximately ε=12%.

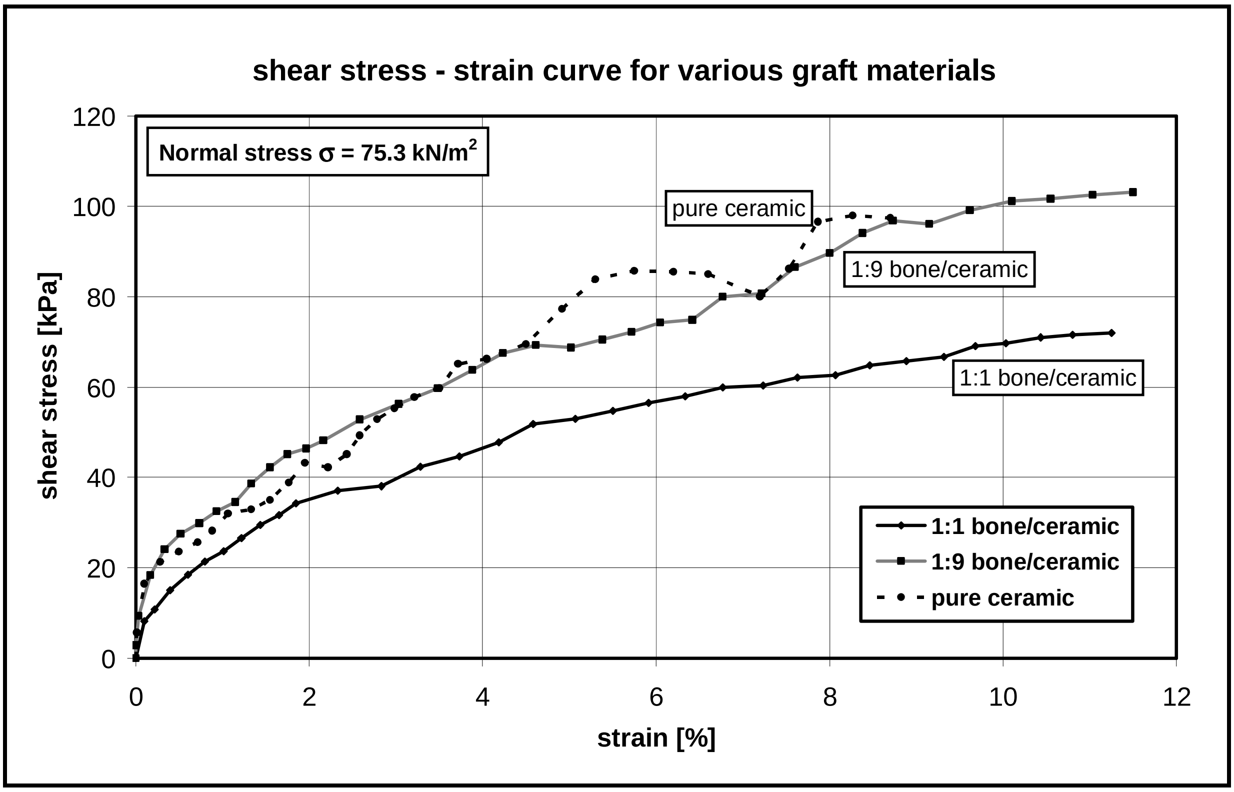

Figure 5.3: *Shear stress versus shear deformation curves for different bone graft materials during shear-box testing.*

In correlation with the stiffness values measured during die-plunger compression testing, pure ovine bone and pure ceramic gave the lowest and highest shear resistance respectively. Both bone/ceramic mixes produced shear-deformation curves lying in between the extremes. The high ceramic content 1:9 bone/ceramic mix could, quantitatively, hardly be distinguished from the pure ceramic. However the mix showed a much smoother stress-strain curve than the pure ceramic which exhibited a jagged profile over its trend curve, an observation resembling the stress-strain behaviour made during the compression of the pure synthetic material. During the experiment the distinct edges in the stress-deformation trace were accompanied by loud noises.

The vertical displacement during shear as a function of horizontal shear deformation is represented in figure 5.4 for pure HA/TCP, the 1:1 bone/ceramic mix and the 1:9 bone/ceramic mix. The graft mix containing equal volumes of bone and ceramic showed negative deformation under shear loading asymptotically approaching a maximum of nearly 0.8mm, equivalent to more than 10% of the maximum shear deformation. The pure HA/TCP ceramic behaved completely different and showed a steady volume increase after a slight initial drop in sample height at about 1.2mm shear deformation. At ca. 2.5mm shear deformation the original sample height was recovered and dilation increased to a maximum value of 0.4mm equivalent to approximately 5% of the maximum shear deformation. As for the the compression testing results, in the shear-test the bone/ceramic mixes combined properties of their pure phases as a function of the mixing ratio. The 1:9 low bone-high ceramic mix exhibited a significant drop in sample height during the early stages of the shear test very much like the equal volumes 1:1 bone/ceramic mix. Towards higher shear deformation that trend reversed and positive dilation occurred similar to that observed for the pure ceramic sample which brought the sample height of the 1:9 bone/ceramic mix back to its original dimension. With a maximum height reduction of ca. 0.4mm at 2.5mm shear deformation, this value was about half what was measured for the 1:1 bone/ceramic mix. Considering that the bone volume fraction was only 10% in the 1:9 bone/ceramic mix, even such a small amount of bone graft had a disproportionally strong effect on the overall properties of the mix, an observation made for graft mixes during die-plunger compression testing as well.

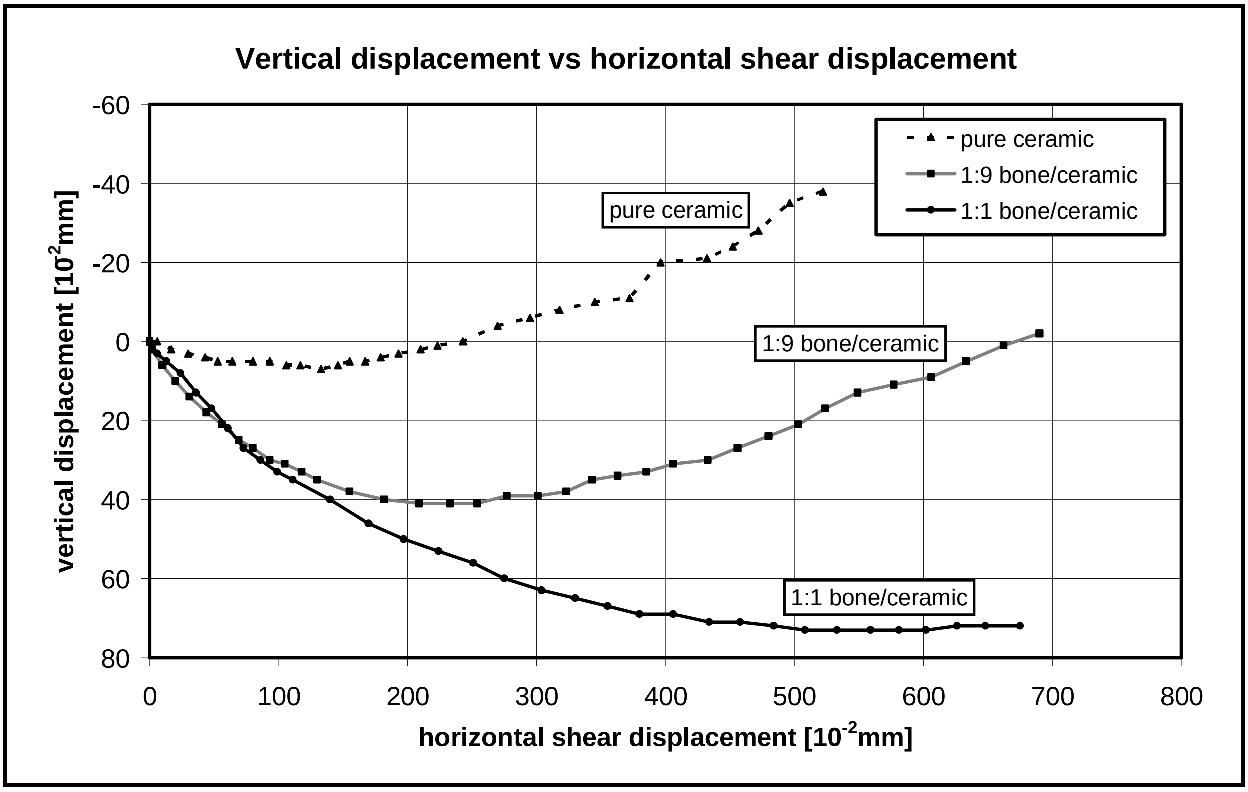

Figure 5.4: *Vertical versus horizontal shear displacement during a shear-box testing of different bone graft materials at a constant medium normal load.*

Using the 1:1 bone/ceramic graft mix as an example, figure 5.5 shows how the shear properties cohesion c and shear angle φ are derived from the shear box experiments using three tests of the graft mix at three different normal loads. For each normal stress the maximum shear stress has measured as the asymptotically reached maximum value shown in figure 5.3 was printed as one data point in figure 5.5. before, by linear extrapolation, the slope and the intersect with the shear stress axis were calculated as shear angle and cohesion respectively.

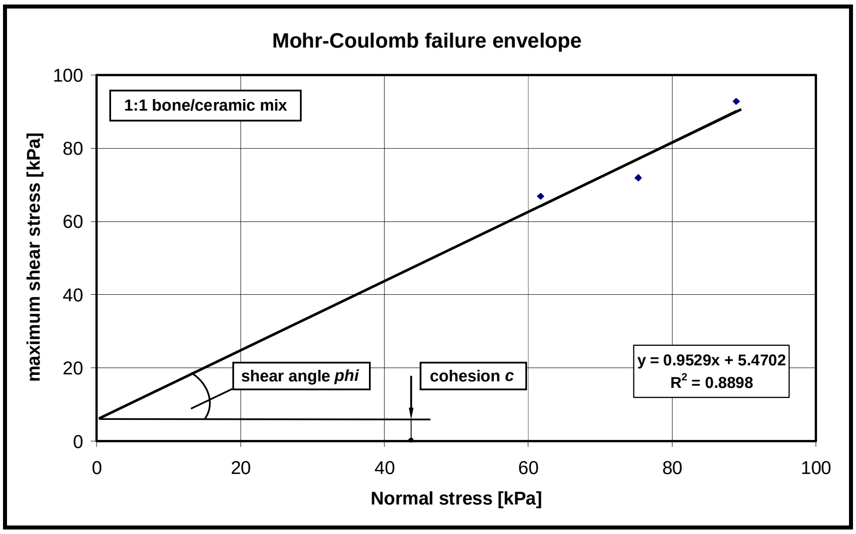

Figure 5.5: *Derivation of the shear properties shear angle φ and cohesion c by extra-polation of the Mohr-Coulomb failure envelope for the 1:1 bone/ceramic graft mix.*

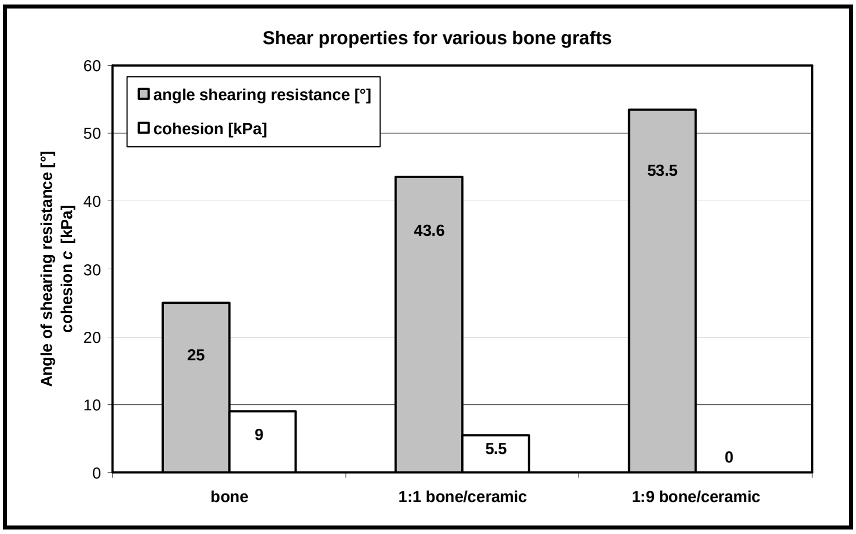

Figure 5.6: *Shear angles φ and cohesion c calculated for pure ovine bone, a 1:1 bone/ceramic mix and a 1:9 bone/ceramic mix.*

Figure 5.6 represents graphically the shear angles *φ* and the cohesion *c* calculated for pure ovine bone grafts and two mixes of ovine bone and 2-4mm diameter granules of 80:20 HA/TCP ceramic at the bone/ceramic mixing ratios of 1:1 and 1:9. Pure ovine bone scored the lowest shear angle measuring *φ*= 25.0° while a shear angle of *φ*= 53.5° was calculated for the high ceramic content 1:9 bone/ceramic mix. For the equal volume graft composition, the 1:1 bone/ceramic mix a shear angle of *φ*= 43.6° was measured, a value right in-between the two extremes indicating a near proportional relationship between mixing ratio and shear angle. For the cohesion *c* derived from the intercept of the Mohr-Coulomb envelope with the shear stress axis, the relationship was reversed. Ovine bone was the most cohesive graft with a value of 9.0kPa indicating comparatively strong internal graft bonding. For the high ceramic content mix no significant cohesion could be identified with c= 0kPa. The equally balanced 1:1 bone/ceramic mix registered a cohesion c=5.5kPa, a value almost half way between the pure bone graft and the high ceramic concentration mix. Both characteristic shear properties, the friction-like shear angle φ and the stiction-like cohesion c were very different for bone graft and the ceramic graft substitute.

5.4 Discussion

With regards to the shear properties, the ceramic bone substitute tested did not mimic the behaviour of bone graft neither qualitatively nor quantitatively, an observation which correlates well with findings from the compression tests. The shear angle φ of bone was the lowest while its cohesion c was the highest of the tested grafts. For the 1:9 bone/ceramic mix, which is close to the pure ceramic's properties, the situation was reversed with a maximum shear angle recorded and a cohesion equal to zero. In comparison to a pure granular ceramic graft, bone contains only a low volume fraction of strong and hard particles in the form of trabecular chips and at the same time includes a high volume fraction of organic tissue like fat and cartilage which does not provide high friction resistance but enhances gliding. When bone grafts are sheared, too few strong particles block slippage while too much organic tissue "lubricates" the shear plane. For pure ceramics or high ceramic content mixes which consist exclusively or dominantly of strong and hard particles and voids, shearing must displace, re-arrange or fracture these particles, first to cause deformation and finally shear failure. Particle re-arrangements and fractures of the ceramic granules were loudly audible during shearing. Little or no quantity of an additional phase like organic tissue is present to reduce the inter-particle friction causing the steep shear angles of those graft materials. The balanced 1:1 bone/ceramic mix showed how those two extreme properties can be combined. Compared to pure bone, the 1:1 b/c mix has a higher volume fraction of hard particles while at the same time a lower organic fraction increased the inter-granular friction and thus the shear-angle. Compared to the pure ceramic or a high ceramic content mix, the organic fraction introduced into the 1:1 bone/ceramic mix provides some cohesion.

The above explanations for the different quantitative shear properties of bone, ceramic and mixes thereof are backed up by the qualitative and quantitative analysis of vertical displacement under shear as shown in figure 5.4. The high organic fraction and the low volume of hard particles in the form of trabecular bone chips cause the sheared sample to sink in because particle re-arrangement is less restricted by hard granules and is aided by lubricating fat or other organic tissue. For pure ceramics or high ceramic content mixes, shearing initially also causes the samples to sink-in slightly as a result of some initial settling and void filling. However this is overcome when shear deformation exceeds values around the graft particle size and subsequently shear deformation forces particles to ride over each other resulting in significant positive dilation as can be seen in figure 5.4. In soil mechanics such behaviour is typical for more densely packed, coarse and non-cohesive materials[206, 220]. Again, the 1:1 b/c mix combines these qualitative characteristics observed for either morsellised bone or granular ceramic. Initially, shearing allows the graft mix to compact aided by the easily compressible and low friction organic phase. Once compacted, further shearing forces the increased volume fraction of hard particles to ride over each other to give way for further shear deformation. As a result dilation occurs compensating for the initial compaction.

5.5 Conclusions

Qualitative and quantitative shear properties of bone grafts and ceramic extender materials are very different from each other so that a granular HA/TCP does not work as a synthetic bone graft on the basis of bone mimicry. Pure granular ceramics offer higher shear angles but lower cohesion values than bone. Shearing causes pure bone grafts to compact while pure ceramic grafts respond to shear with positive dilation. In a bone/ceramic mix these quantitative and qualitative properties can be combined to create a mechanically improved graft material for impaction grafting. This conclusion corresponds well with data analysis from the die-plunger compression tests and shows that both simple and standardised fundamental test procedures can efficiently derive relevant information about graft properties. A bone/ceramic graft mix offers higher shear angles and thus higher total shear resistance than pure bone while retaining some cohesion beneficial for intra-operative handling. Thus with regards to shear properties, bone/ceramic graft mixes can be recommended for surgical use.

High cohesion values like those found in pure bone dominate overall shear resistance when the normal stress is uni-axial (σ_3= 0 with reference to figure 5.5), a condition different from the multi-axial loading situation of bone graft in an impaction grafted femur. However some graft cohesion is required for graft handling and packing by the surgeon. Grafts like pure ceramics which do not cohere, do not stay in place when intra-operatively inserted into the medullary canal. Its horizontal position on the operating table causes grafts to fall out unless sufficient cohesion and adhesion bonds the graft to itself and the endosteal wall. Graft lost and left in the wound can cause post-operative complications

Adding even small amounts of bone graft to granular ceramic extender strongly influenced the qualitative shear properties as the vertical shear deformation for pure ceramic and the 1:9 bone/ceramic mix showed. With only 10 vol.-% of bone graft in the mix, under shear the samples compacted by approximately half as much as the 1:1 bone/ceramic mix, a phenomenon hardly visible for the pure ceramic at all (figure 5.4). Despite the volume increase measured towards higher strain rates the original sample height was never exceeded. The dominant effect of even small bone fractions on a graft mix indicates that surgeons can use even high fractions of synthetic ceramic graft to extend bone without sacrificing too much of the qualitative characteristics of pure bone graft. Adding ceramic granules to bone enhances the shear properties while no risk of too high concentrations can be identified. Again this is a conclusion also drawn from the compression properties derived during die-plunger testing.

The reduction of negative dilation for bone and bone/ceramic mixes when the ceramic fraction is increased also offers a potential stability advantage in the clinical loading situation. If negative dilation under shear deformation is high it causes further compaction of the graft in the contained environment of the medullary canal. This phenomenon could aid vertical stem subsidence. This effect might be reduced when the graft is intensively impacted into the femoral canal prior to stem cementation, an argument highlighting again the crucial role of impaction as the most influential factor for achieving mechanical stability in clinical impaction grafting. Using ceramic granules to extend a bone graft or graft mix reduces the negative dilation under shear and thus could reduce the sensitivity of graft stability to impaction levels. This way, surgeons in fear of femoral fracture due to excessive impaction forces could still achieve stable grafts. Positive dilation as measured for the pure ceramics would be suppressed in the constrained environment of an impaction grafted femur. This could either stabilise the graft by increased normal and friction forces but might also increase loads onto the constraining femoral canal eventually leading to fracture.

Only a few graft materials and only a low number of samples per material were tested using the shear box experiment. This was the consequence of the very high graft consumption and the high tolerances and the inherent systematic errors of the shear-box tests. With the minimum volume required for the derivation of the least accurate extrapolation of shear angle and cohesion, alternatively, more than 60 compression tests (chapter 4), 12 ovine model (chapter 6) or 6 human model endurance tests (chapter 7) could be conducted. Considering the high value and limited availability of human graft and the prototype ceramic extender and the long preparation time required for xenografts, more tests did not seem justified. The meaning of the quantitative comparison of the shear test results must also be interpreted with care as the soil testing apparatus and procedure produces some systematic errors which make it possibly not optimal for testing bone grafts. Soil mechanics theory is based on the idealised assumption that the extension of a particulate aggregate is infinitely large against the granule size. As a consequence, mechanical tests of soils such as the shear box require that the constraining dimensions of the testing device are at least ten times larger than the largest granules contained in the sample itself. With some trabecular bone chips exceeding 10mm in size, a shear box measuring 60mm×60mm would be too small to allow shear angle and cohesion to be measured as overall properties of a homogenously mixed bulk particulate aggregate. This is the smallest shear box and it is normally used for fine sands. The relevance of shear angle and cohesion as overall properties of an idealised graft for the mechanical performance in impaction grafting must be questioned altogether because the dimensional relationship in the clinical scenario is even much more dissimilar to the assumptions made in soil theory and the requirements demanded for shear box testing. The gap width between femoral canal and cemented stem can be below 10mm so that some particles could not fit or individual particles would be responsible for the load transfer between stem and femur. Under these circumstances no particulate aggregate can form homogenously so that shear angle and cohesion as characteristics of a particulate matter with theoretically unlimited expansion seem irrelevant. The problem of high graft consumption, low result accuracy, experimental error and weak congruence between test and clinical conditions make the shear box test less valuable as a tool for bone graft analysis.

However, the tests conducted in this study allowed an insight into the qualitative shear properties of the bone grafting materials of extreme configurations. Highly different cohesion, shear angle and dilation helped to understand the load transfer mechanisms and derive clinical consequences. The shear box might be too inaccurate and of too low practical relevance to resolve fine graft differences such as sintering temperature of the ceramic phase but it can still be recommended to qualitatively reference a newly developed synthetic graft to the gold standard bone. The main findings can be summarised in table 5.1.

- Shear properties of bone graft and ceramic substitutes are very different qualitatively and quantitatively.
- Bone has maximum cohesion and minimum shear angle.
  while ceramic has maximum shear angle and no cohesion.
- Shear deformation causes bone to compact while ceramic shows positive dilation.
- Differences are the result of the multiphase nature of bone graft comprising hard cancellous bone chips plus compressible and lubricating soft tissue while the ceramic consists of hard and strong but brittle granules.
- Combining bone and ceramic in a graft mix led to a combination of the individual properties depending on the mixing ratio.
- Even small bone fractions in a graft mix disproportionally dominate the overall properties indicating the strong effect of soft tissue compressibility and lubrication.
- Bone/ceramic mixes had higher shear resistance, e.g. superior mechanical properties to pure bone.
- Bone substitution with ceramic grafts does not work on the basis of bone mimicry.
- Ceramic bone substitutes can be used as graft extenders only.
- Ceramic bone graft extenders can be mixed into bone graft at very high ratios to increase shear resistance. Only some cohesion should be retained for surgical handling.
- Ceramic particles in a bone/ceramic mix reduce negative dilation which in the constrained geometry of an impaction grafted femur can reduce subsidence under shear.
- Findings from shear-box testing correlate well the results from die-plunger compression.
- Shear-box tests require very high graft volumes.
- The low ratio between shear-box length and bone particle size introduces a systematic error.
- Shear-box tests derive properties for a bulk particulate aggregate with extensions large against particle size, a condition, which does not correlate with the dimensional constraints in impaction grafting.
- Shear-box tests give only limited insight into the mechanical graft properties relevant for impaction grafting. It cannot be recommended as an efficient and sensitive basic test method for deriving quantitative mechanical graft properties.

Table 5.1: *Summary of main findings derived from shear testing.*