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Abstract

For the modelling of the thermalmechanical interaction between ceramic breeder and beryllium pebble beds and the structural material in ceramic breeder blankets, the characteristic properties of these pebble beds in the relevant temperature and pressure ranges must be known.

Uniaxial compression tests with monosized and binary beryllium pebble beds were performed in a temperature range between ambient temperature and 480 °C and pressures up to 8 MPa. Empirical correlations for the moduli of deformation were elaborated for the different bed types and first measurements for thermal creep are presented. Stress-strain relations depend sensitively on the initial state of the bed and with this on the filling procedure. This is of special importance for binary beds where it must be ensured that a homogeneous distribution of small pebbles in the bed is obtained.

First results from triaxial compression tests for monosized and binary beds are reported. The internal friction of these beds is significantly larger than that of beds with particles with smooth surfaces.

Experimentelle Untersuchung der Eigenschaften von mono-dispersen und binären Beryllium-Schüttbetten

Zusammenfassung

Zur Beschreibung der thermomechanischen Wechselwirkung zwischen keramischen Brutmaterial- und Beryllium-Schüttbetten und dem Strukturmaterial in Blankets mit keramischen Brutwerkstoffen müssen die charakteristischen Eigenschaften dieser Schüttbetten im relevanten Temperatur- und Druckbereich bekannt sein.

Es wurden Uniaxiale Kompressionsversuche mit monodispersen und binären Beryllium-Schüttbetten durchgeführt in einem Temperaturbereich zwischen Umgebungstemperatur und 480°C und maximalen Drücken bis 8 MPa. Empirische Korrelationen für die Deformationsmoduli der verschiedenen Bett-Typen wurden erarbeitet und erste Messungen zum thermischen Kriechen werden vorgestellt. Die Spannungs-Dehnungs-Beziehungen hängen empfindlich vom Ausgangszustand der Schüttungen ab und damit von der Füll-Prozedur. Dies gilt besonders für binäre Betten, bei denen sichergestellt sein muß, dass eine homogene Verteilung der kleinen Partikel im Bett erreicht wird.

Erste Ergebnisse aus Triaxial-Versuchen mit monodispersen und binären Beryllium-Schüttbetten werden vorgestellt. Die innere Reibung dieser Betten ist deutlich größer als diejenige von Schüttbetten mit Partikel mit glatten Oberflächen.

CONTENTS

1. INTRODUCTION

Ceramic breeder blankets consist of ceramic breeder and beryllium pebble beds; the latter are needed for neutron multiplication. For the ITER breeding blanket [1] binary beryllium pebble beds are foreseen, consisting of large pebbles of about 2 mm diameter and small pebbles between 0.15 and 0.25 mm. During operation, stresses arise due to different thermal expansions of the structural and the pebble bed materials, pebble bed swelling and thermal creep. These stresses cause deformations of the pebble beds because of pebble rearrangements into a denser configuration, pebble failure, and elastic and plastic deformations of pebbles which increase the contact areas between pebbles. The latter is of importance for the heat removal by conduction in the pebble bed.

This stress build-up jeopardises the safe blanket operation if the mechanical integrity of the blanket element is endangered or if heat and tritium removal are significantly deteriorated due to pebble breakage or melting.

In order to describe the thermomechanical behaviour of a blanket element, finite element codes are used with appropriate models for the description of pebble beds. As input, these models require data on characteristic pebble bed properties determined in standard-type tests currently used in soil mechanics.

Of prime importance are uniaxial compression tests (UCTs). In these tests, an axial force is exerted on the top of a pebble bed contained in a cylindrical cavity (details given in Section 2.1) and the relationship between the axial stress within the pebble bed (identical to the axial pressure) and the axial strain is determined. Keeping the pressure constant at elevated temperatures, such an apparatus is also used to measure thermal creep strains.

For the description of the macroscopic movement (flow) of pebbles, triaxial compression tests (TCTs) are additionally required which provide information on the inner friction angle of the pebble bed. In these tests, cylindrical pebble beds are subjected to an increasing vertical pressure (resulting in a vertical strain), while at the same time the horizontal pressure is kept constant and the bed is allowed to deform in the horizontal direction, for details, see Section 2.2.

Prior to the present investigations, no relevant data from UCTs and TCTs existed for beryllium pebble beds. There is a considerable amount of UCT data for different ceramic breeder materials [2-4], an overview is given in [5]. The original aim of the present investigations was to generate data for binary beds for temperature and pressure ranges characteristic for the ITER breeding blanket. However, results from measurements with monosized beds are also presented which might become of interest for future blanket concepts.

2. EXPERIMENTAL

2.1 Uniaxial compression test (UCT) apparatus

The handling of Be pebble beds required the construction a new test facility installed in a glove box. This glove box consisted of 3 parts: the lock, the storage area and the experimental area. Storage and experimental areas were connected with a rail system to transport more easily components from one side to the other. The helium gas (pressure: slightly subatmospheric) in the glove-box was circulated to a cooling system in order to limit the temperature increase during operation at the top of the glove box to about 60°C.

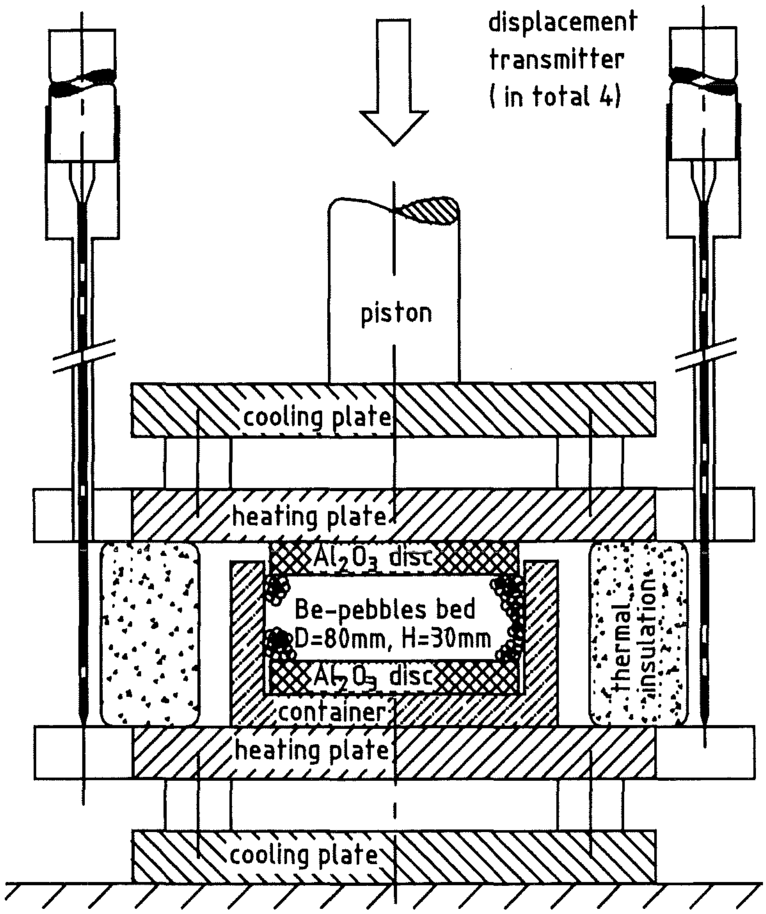

Figure 1. Set-up for UCT

Figure 1 shows schematically the press (Fa Weber, Germany) with the most relevant parts of the UTC: The granular material was filled in a circular stainless steel cavity with an inner diameter of 80 mm and an inner height of 45 mm, see Fig. 2. Al_2O_3 discs were used at the top and the bottom (as in previous experiments 2-3]) because of the good compatibility with the granular material (no fritting together) and the large surface hardness. Bed heights of about 43 mm were investigated. The small ratio of bed height to diameter ensured that the wall friction does not affect remarkably the results.

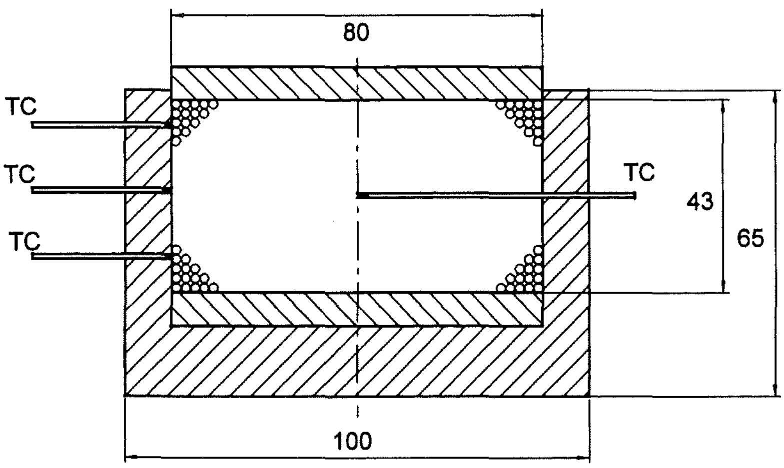

Figure 2. Pebble bed container

The pebble bed was heated from the top and the bottom to constant temperature levels by temperature controlled heating plates; the adjacent cooling plates were required to avoid the heating-up of other parts of the facility. The pebble bed container was thermally insulated by a removable insulator in order to keep heat losses small.

The bed temperature was determined by three thermocouples installed in the container wall. An additional thermocouple in the middle of the pebble bed was only used for an operational test, see Section 2.4.

The bed strains were measured by four inductive displacement transducers positioned outside the high temperature zone by using quartz rods and tubes, see Fig. 1. During the experiments at the highest temperatures of ≈ 480°C, the transducer temperature was ≈ 60°C. The use of 4 displacement transducers proved to be very beneficial for the control of the parallelisms of the top Al_2O_3 disc during operation.
The pressure exerted axially on the pebble bed was measured via a pressure transducer in the hydraulic system, calibrated in a previous experiment with a load cell between piston and container lid. The measured signals were processed by a data acquisition system (MEMESS) and stored in a PC.

2.2 Triaxial compression test (TCT) apparatus

The TCT-apparatus developed for the present experiments is schematically shown in Fig.3. The pebble bed is filled in a cylindrical cavity of 60 mm diameter where the cylindrical wall consists of solid polyethylenglycol (PEG) separated by a rubber membrane from the pebble bed. This PEG annulus is connected via a sight glass to a gas system. After filling-in the pebble bed, a controlled gas pressure p_2 is applied and the PEG is melted (melting point≈ 40°C) by heating up the container with the heating plates of the press. During axial compression, PEG is displaced into the sight glass. Originally, it was anticipated to use the measurement of the PEG height in the sight glass for the determination of the change of the

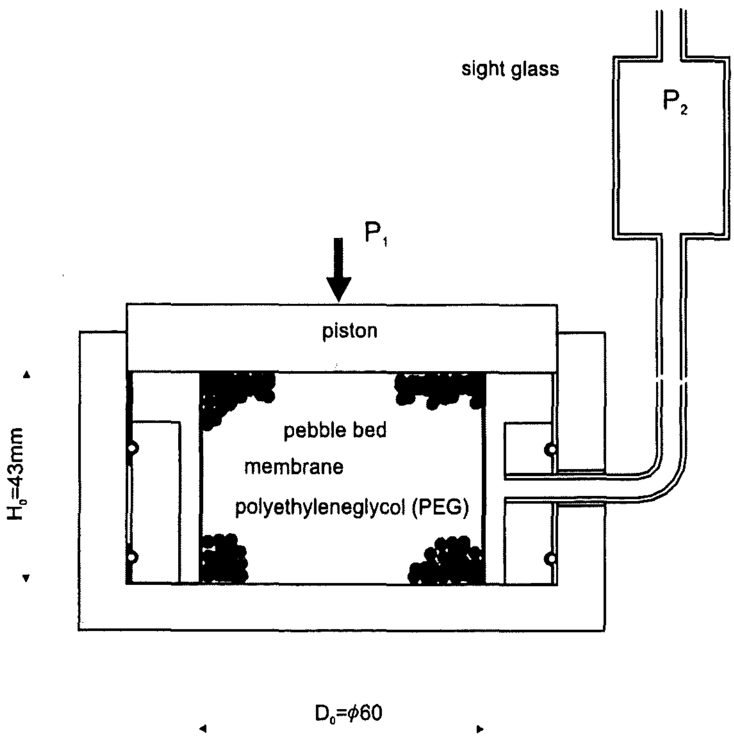

Figure 3. Schematic of TCT apparatus

bed volume during compression. However, operational tests proved that the measurement accuracy was not satisfacty and the sight glass was replaced later by a small steel container. After termination of the TCT, the system was cooled down in order to freeze the PEG such that the shape of the pebble bed surface at the end of the TCT could be visualised.

2.3 Characteristics of beryllium pebbles

The beryllium pebbles, fabricated by Brush Wellman, consisted of pebbles with nominal diameters of 2 mm and 0.1 0.2 mm diameters. The larger size pebbles were obtained as a product generated in an intermediate step used in the processing of Be ore. In this step, beryllium fluoride is reduced with magnesium metal to molten beryllium and magnesium fluoride. Upon cooling, a solidified cake of beryllium spherical pebbles, magnesium fluoride and unreacted beryllium fluoride is formed. The solid cake is crushed in a hammer mill and leached with water to remove the beryllium fluoride and most of the magnesium fluoride. A density separation step is used to separate the approximately spherical Be particles from the residual magnesium fluoride. Sieving is used to provide spherical particles of the required sizes for test purposes.

The large pebbles are approximately of spherical shape with indentations on the surface and a variety of coarse pores, with some pebbles having large voids as shown in Fig. 4. Most pebbles have a very small micro-porosity that is usually oriented along the crystal axis showing a very fine dendritic or cellular structure, for details, see [6,7].

The small (0.1-0.2 mm) Be pebbles were made by inert gas atomization and centrifugal atomization. These processes involve break-up and rapid cooling of a molten metal stream to form a powder with purity levels comparable to that for other commercial Be products. In general, the porosity of the small pebbles is always smaller than that of the large pebbles. Metallographic structure of both small and large pebbles shows the presence of large grains, in some cases as large as the pebble diameter [6,7]. Figure 5 shows that the small pebbles are by far less regular than the large ones and it can be imagined that during filling the small pebbles do not flow easily through the gaps between the large pebbles.

Figure 4. Large beryllium pebbles

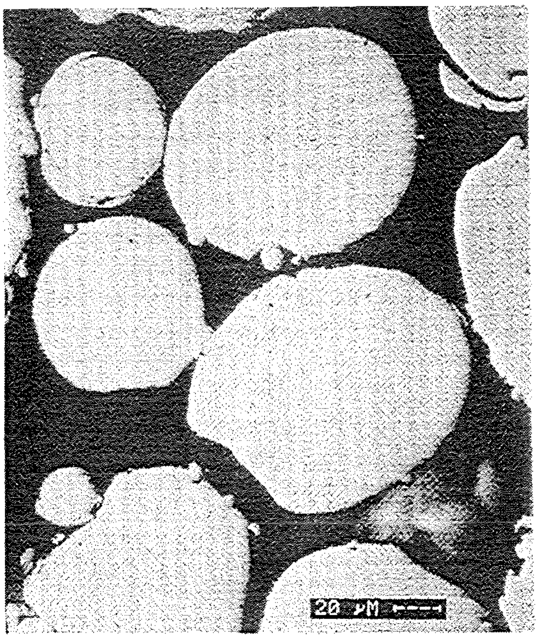

Figure 5. Small beryllium pebbles

2.4 Experimental procedure

Prior to the performance of the experiments, several operational tests were performed:

- In order to determine the required time period to reach steady-state temperature conditions in the pebble bed an additional thermocouple was used to measure the temperature in the middle of the bed, see Fig. 3. It proved that steady-state conditions were reached after heating-up periods of about 3 hours and the differences between the middle of the pebble bed and wall were about 2 °C. The inner thermocouple was removed in the subsequent experiments in order to avoid a disturbance of the bed.
- In order to check the drift of the displacement transducers during experiments at elevated temperatures an experiment at 470°C without pebbles in the container was performed. No significant drift was observed during a time period of ≈ 30 hours which is characteristic for the thermal creep investigations.
- An UCT with a Li_4SiO_4 bed was performed (see Section 3.1) which gave the same results as obtained in another test facility [4].

In the course of the experiments, several improvements were made, some of them are listed below:

- The container was exchanged with a hardened version.
- The metallic lid was replaced by Al_2O_3 lid.
- In first experiments the beds were slightly compressed during the heat-up phase in order to have a heating-up from both sides. This procedure, however, results in an initial compression of the bed which influenced significantly the results obtained in the subsequent UCT. In latter experiments, therefore, the heating-up was performed with a small gap between piston and lid.

Due to these modifications, a repetition of several experiments was required. In the following, only those experiments are discussed which were performed when these modifications had been made. Characteristic data of the experiments are shown in Table 1.

Table I. Characteristic data of the experiments

	p (MPa)	T (°C)	γ_L (%)	γ_s (%)γ	Sw.up (%)	H (mm)
M5	8	T_a	60.4			36.7
M6	8	T_a	60.4			36.7
M7	8	T_a	60.4			36.7
M8	8	T_a	59.1			38.0
M9	8	T_a	59.1			38.1
M10	8	T_a	59.2			38.3
M11	8	T_a	59.2			38.3
M12	8	T_a	59.2			38.3
M13	8	T_a	59.2			38.3
M14	8	T_a	59.2			38.3
M15	8	T_a	59.6			38.5
M16	8	470	60.2			38.1
B11	8	400	58.8	18.4	1.0	38.5
B12	8	T_a	57.6	18.3	1.0	38.4
B13	8	T_a	57.7	18.3	1.2	38.3
B14	8	400	58.2	18.8	1.3	37.2
B15	8	T_a	59.6	18.6	1.0	39.8
B16	8	445	59.2	18.7	1.0	39.7
B17	6	445	59.4	18.6	1.0	39.8
B18	4	440	59.3	18.5	1.3	39.6
B19	6	400	59.5	18.6	1.0	39.5
B20	6	480	59.6	18.4	1.3	39.7
B21	4	480	58.4	18.5	1.3	39.6
B22	8	T_a	58.8	3.5	0.0	39.3
B23	8	T_a	58.9	10.6	0.3	39.4
B24	8	T_a	59.1	13.8	0.5	39.1
B25	8	480	59.9	18.8	1.3	39.2
B26	6	470	59.8	18.6	1.0	39.3

For the investigations of monosized beds (MB), the large pebbles were filled in by knocking simultaneously with a small hammer or a screwdriver at the container wall in order to obtain a dense packing. After putting the lid on the top, the container was positioned in the press and the piston was moved towards the lid until a pressure increase of about 0.2 MPa was reached. In this position the initial bed height H_0 was determined and the UCT was started.
For the production of binary beds (BBs) the container filled with the large pebbles was removed from the press and the small pebbles were filled in. Due to the roughness of small and large pebbles again some slight knocking was needed to reach high filling factors. Great attention was directed to avoid that the large pebbles changed their position because in this case the small pebbles slipped easily between the large ones and the large pebbles did swim up. In practice, this swimming-up could not be totally avoided: for small pebble filling factors (ratio of pebble volume to total volume) of $\gamma_s \approx 18\%$, a bed swimming-up of ≈ 1-1.5 % occurred. The initial bed height for binary beds H_o was determined after this filling procedure, characteristic data of the experiments are given in Table I. Further aspects of the filling factor are discussed in Chapter 5.

An interesting observation was made during these filling procedures by pressing by hand excentrically on the upper Al_2O_3 disc on the bed: the MBs behaved much stiffer than the BBs where the bed yielded more easily. It appeared that the small pebbles behaved like ball bearings between the large pebbles. A strong movement of particles has to be avoided during filling because of unfavourable dilatance effects, see Section 4. Therefore, no initial pressure was exerted on the bed before starting the experiment.

RESULTS FROM UNIAXIAL COMPRESSION TESTS (UCTs)

Figure 6 shows a characteristic result of an UCT at elevated temperatures: the axial compressive stress (identical with the vertical pressure exerted on the bed) is shown as a function of the axial compressive strain (ratio of axial displacement (mean value from the four displacement transmitters) to initial bed height). After having reached steady-state temperature conditions, the pressure was increased during a time period of about 30 min to the selected maximum value. Then, the pressure was decreased to zero during a time period

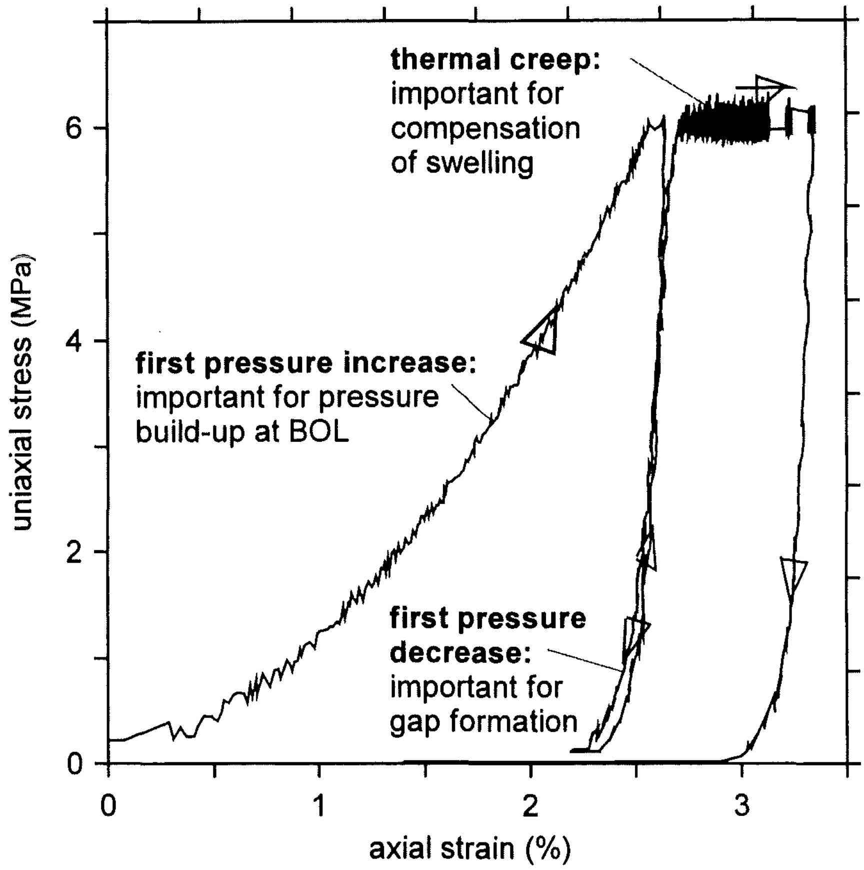

Figure 6. Characteristic UCT at elevated temperature (binary bed, T=480°C)

of about 15 min, increased again to the maximum value, and kept constant for a given time period for the measurement of thermal creep. At the end of the experiment, the pressure was decreased to zero again. The characteristic parts of an UTC are:

- *The first pressure increase , (curve "1st pi"):* this curve is caused by the irreversible displacement of particles forming a denser configuration plus some elastic and maybe plastic deformation of particles.
  For the description of the thermomechanical interaction between pebble beds and the structural material the knowledge of this curve is of prime importance because it determines the pressure build-up during the first blanket operation.
- *The first pressure decrease (curve "1st pd")*, and *second pressure increase (curve "2nd pi"),:* the slope of the curve "1st pd", and the subsequent stress increase are much steeper than the slope of curve "1st pi" because these curves are caused mainly by elastic deformations. The hysteresis is characteristic for the influence of internal friction. For further cycles, these curves do not differ significantly.
  The difference between the curves *"1st pi "* and "1st pd" is relevant for the formation of gaps which might form during blanket operation.

- *Creep strain*: keeping the stress constant at a given value, the strain increases with time due to thermal creep. The knowledge of thermal creep is important for the relaxation of stresses during the first days of blanket operation and for the compensation of swelling due to irradiation which occurs during long operational time periods.
- Cycling at the end of the creep period might show that the bed stiffness has increased slightly due to the enlarged contact areas between individual particles because of creep. This effect is not expressed in the present experiments due to the small creep rates experienced.

3.1. Stress-strain relationships for 1st pressure increase

In the following, results are presented on the relationships between uniaxial stress, σ, and strain, ε, for the 1st pressure increase. From these relationships the moduli of deformation E are determined, see Section 3.3.

3.1.1. Monosized pebble beds (MBs)

Figure 7 shows the stress-strain dependence for all experiments performed with MBs. For ambient temperature, there is a certain scattering of the data which is caused by an initially non-perfect horizontal bed surface (it should be kept in mind that already bed height differences of 0.2 mm correspond to 0.5 % strain difference) or by the influence of small differences in the filling factor.

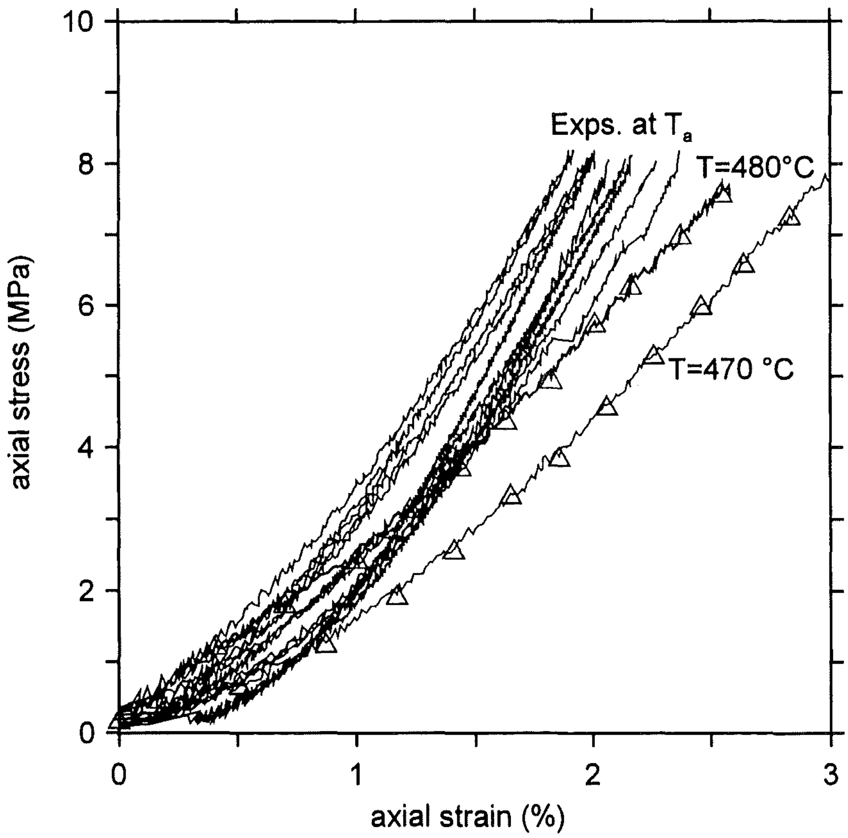

Figure 7 Monosized bed: first pressure increase

Figure 7 contains also data from two experiments at high temperatures. From these data it might be concluded that with increasing temperature the beds become "softer" (larger strains for a given stress). Such a tendency was observed for ceramic breeder materials [2-5], however, at temperatures above 600 °C. More experiments at elevated temperatures are required in order to decide if a real temperature effect exists or if the data are within the scattering range which is, at least for binary beds, significantly larger at elevated temperatures than at ambient temperature, see below.

Due to the lack of data, a temperature effect is not assumed in the present stage. A relationship of the type

$$\sigma(\text{MPa}) = A\ \varepsilon(\%)^n \qquad (1)$$

is used to fit the data. As a mean curve, the results from Exp. No. M13 are used and the following values are obtained: $A_{MB,i} = 1.89$; $n_{MB,i} = 1.89$.

3.1.2 Binary pebble beds (BBs)

Figure 8 presents results for the 1st pressure increase for BBs at ambient temperature. The data scattering is similar to that of the corresponding tests with MBs, however, the beds are distinctively softer. This softer behaviour might be explained by the "ball bearing" effect of the small pebbles, mentioned above, which enables the bed to rearrange more easily into a denser configuration.

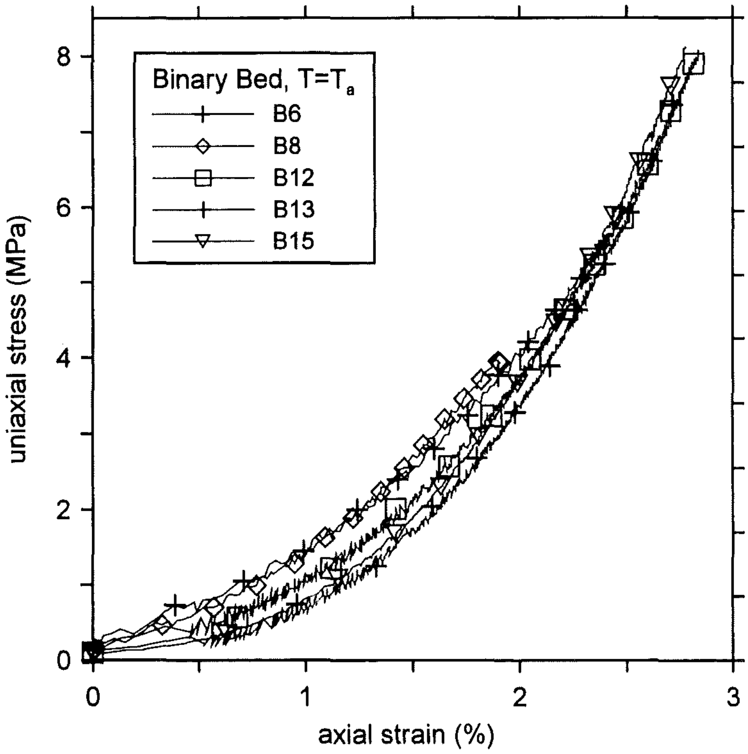

Figure 8. Binary beds; first pressure increase

The data scatter of the experiments at elevated temperatures is much more expressed as shown in Fig. 9. This might be caused by the fact that during heating-up a nonuniform local rearrangement of pebbles causes small inclinations of the Al_2O_3 top disc on the bed surface. Analysing in more detail the signals of the four displacement transmitters, the tendency is observed that "stiff" stress-strain curves (small strains for a given stress value) are measured in those experiments where the inclination of the top disc changes most during pressure increase. Figure 10 shows an example: the differences of the individual displacements in Exp.No. B25 (stiffer curve) are larger than those of Exp. No B26. Those experiments where the top disc inclined less are assumed to be more valid; i.e. the beds with the softer stress-strain dependence. Comparing Figs 8 and 9, again, the tendency could be deduced that the curves become softer with increasing temperature.

Because of the small differences, this temperature effect is neglected for the investigated temperature range.

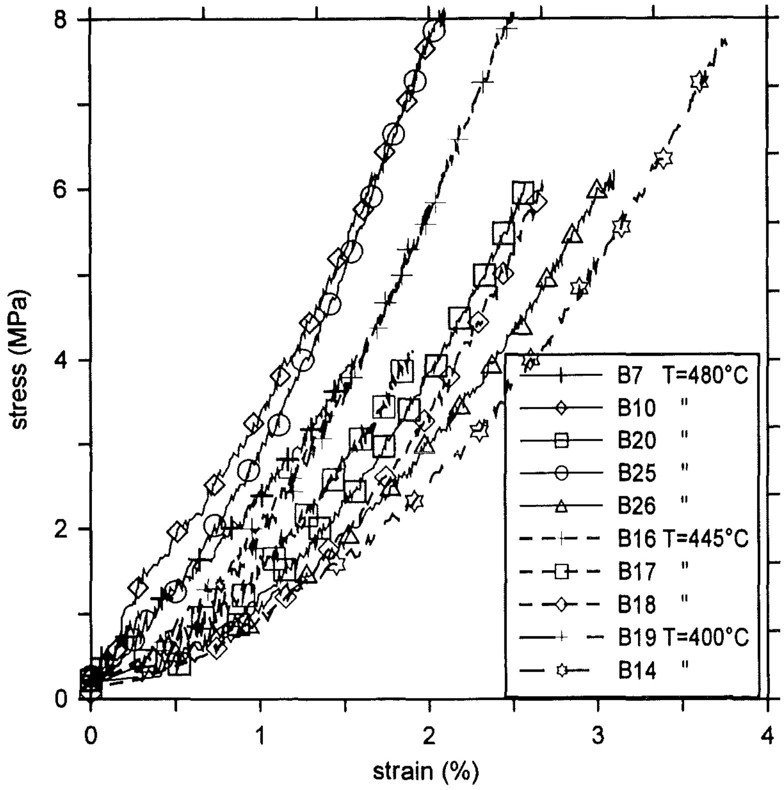

Figure 9. First pressure increase for the experiments at elevated temperatures

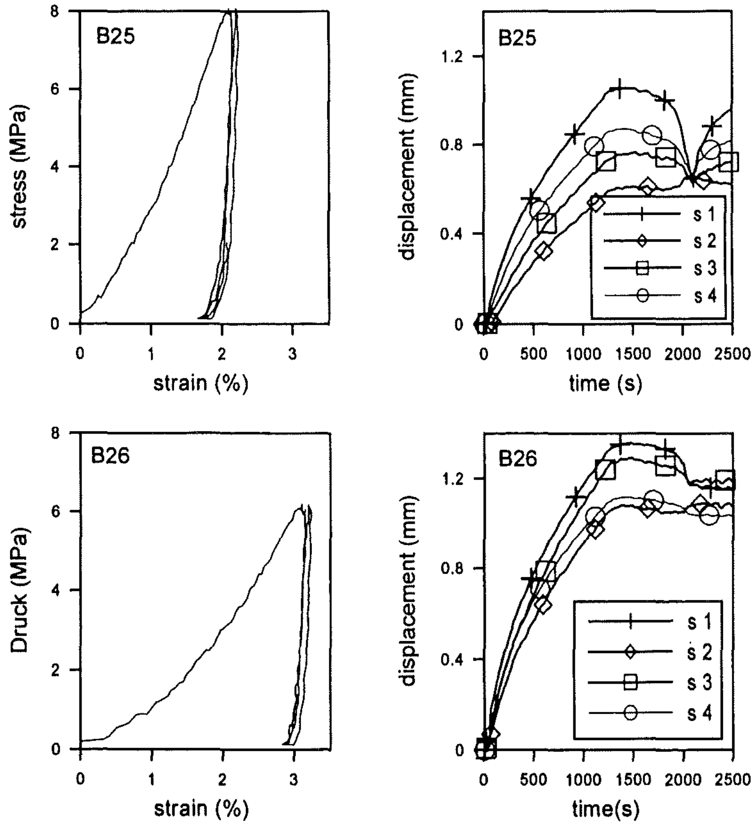

Figure 10. Individual displacements for Exps. B25 and B26

As a mean curve, the data from Exp. No B26 are considered. Using again relationship (1), it follows: $A_{BB,i}$ = 0.80 and $n_{BB,i}$ = 2.08.

In order to investigate the influence of different filling factors of the small pebbles some additional experiments were performed with small values of γ_s, see Fig.11: the increase of the "softness" of the beds with increasing γ_s is clearly seen.

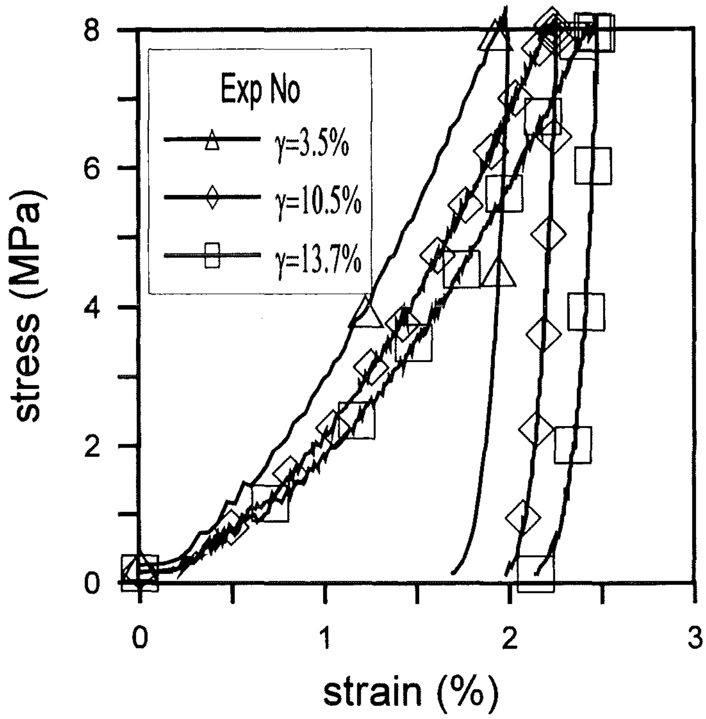

Figure 11 Influence of filling factor γ_s on stress-strain relation

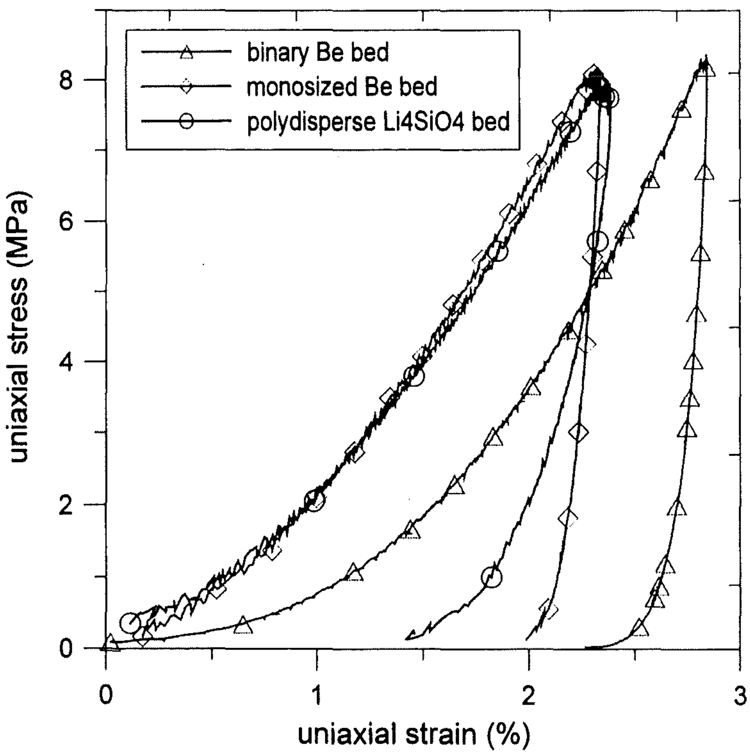

Figure 12. UCTs of a monosized and a binary Be bed and a polydisperse Li_4SiO_4 bed

Figure 12 shows a comparison of UCTs with a monosized and a binary beryllium bed, and a polydisperse Li_4SiO_4 bed [4] (pebble diameters between 0.25 and 0.6mm). The stress-strain dependences of the 1st pressure increase are quite similar for the monosized Be bed and the Li_4SiO_4 bed. The slope of the curves of the pressure decrease is steeper for the Be beds than for the Li_4SiO_4 beds which might indicate that for the beryllium beds the pebbles are plastically deformed during the pressure increase (for Li_4SiO_4 a plastic deformation can be excluded for $T = T_a$).

3.2. Stress-strain relationships for 1st pressure decrease

The slope of the 1st pressure decrease is much steeper than the slope of the 1st pressure increase as already demonstrated in several figures. Characteristic results for both MBs and BBs are shown in Fig. 13. For a better comparison, all curves were shifted to a common starting point of 0.4 % for σ_{max} = 8MPa. There is no distinct difference between MBs and BBs. Using again relationship (1) for an average curve through $\sigma = 0$ at $\varepsilon = 0$, the values $A_{BB,i}$ = 68.9 and $n_{BB,i}$ = 2.86 are obtained.

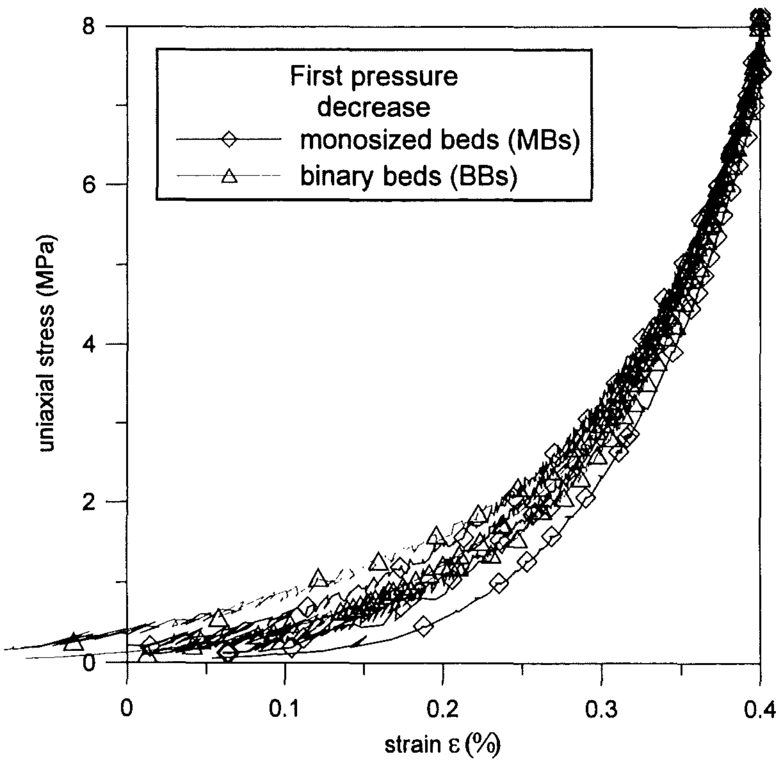

Figure 13. First pressure decrease for MBs and BBs (starting at $\varepsilon = 0.4$ for σ = 8 MPa)

The relationship for the 2nd pressure increase differs negligibly from that for the 1st pressure decrease, see Fig. 6. As already mentioned, there is a small hysteresis between increases and decreases due to the influence of friction between pebbles.

3.3 Moduli of deformation

The aim of the experiments is to provide computer codes for the description of the thermomechanical interaction between pebble beds and structural materials with empirical correlations for the stress-strain relations.

In soil mechanics, often the ***uniaxial modulus of deformation*** is used, defined by the ratio of stress to strain, E(MPa) = σ(MPa)/ε(1), or with the corresponding incremental values, $E^* = \Delta\sigma/\Delta\varepsilon$.

Characteristic for granular materials is a power law dependence of the type:

$$E = C\sigma^m . \tag{2}$$

Then, the modulus E* only differs from E by the factor 1/(1-m):

$$E^* = C(1-m)^{-1}\sigma^m . \tag{2a}$$

These moduli of deformation are determined directly from the stress-strain relationship (1) by

$$C = 100A^{1/n} \;,\; m = 1-1/n . \tag{3}$$

Figure 14 shows results for the modulus of deformation, E, for the 1st pressure increase for the MBs and BBs. The agreement between fit and experimental data is quite well except at very low stresses which are not of large practical importance.

Table II summarises the values of the fit parameters. As already mentioned, these values are recommended to be used in a temperature range between ambient and about 500°C where a distinct temperature effect was not found experimentally. At higher temperatures, the modulus of deformation for the 1st pressure increase should become smaller, similar to the tendency observed for ceramic pebble beds [4].

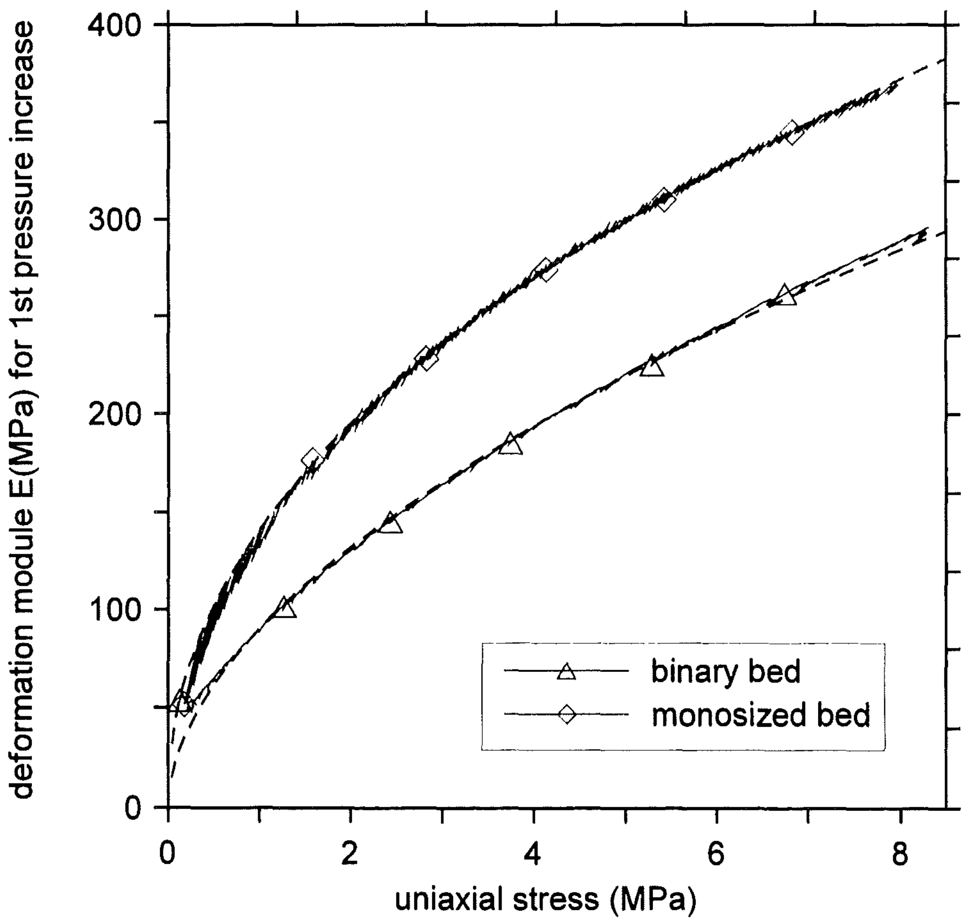

Figure 14 Moduli of deformation for 1st pressure increase for MB and BB

Table II: Moduli of deformation, E

	MB		BB	
	m	C	m	C
first pressure increase "i"	0.47	140	0.52	90
first pressure decrease "d"	0.65	440	0.65	440

3.4. Thermal creep

Keeping the pressure constant at elevated temperatures, the strain increases with time. Modelling the creep strain rates of pebble beds is different from that of homogeneous materials because the contact zones between pebbles change with time. Therefore,

$$d\varepsilon_{creep}/dt = f(\text{material properties, T, p, t}).$$

The results for the creep strains are summarised in Figs. 15 and 16. The main result is that

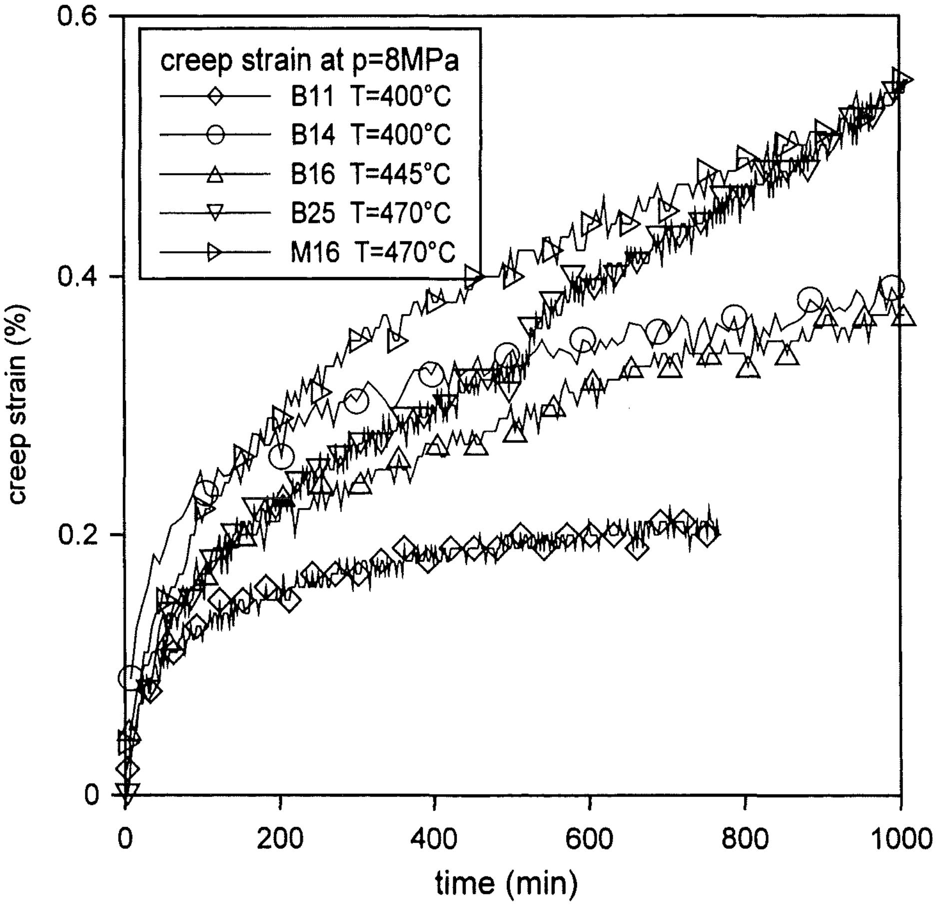

Figure 15. Thermal creep strain at p = 8 MPa

for the investigated parameter range creep strains are very small. Due to these small values measurement inaccuracies are large and the data are not always consistent with respect to the expected influences of temperature and pressure. Creep should increase both with pressure and temperature(for beryllium pellets the pressure dependence is very

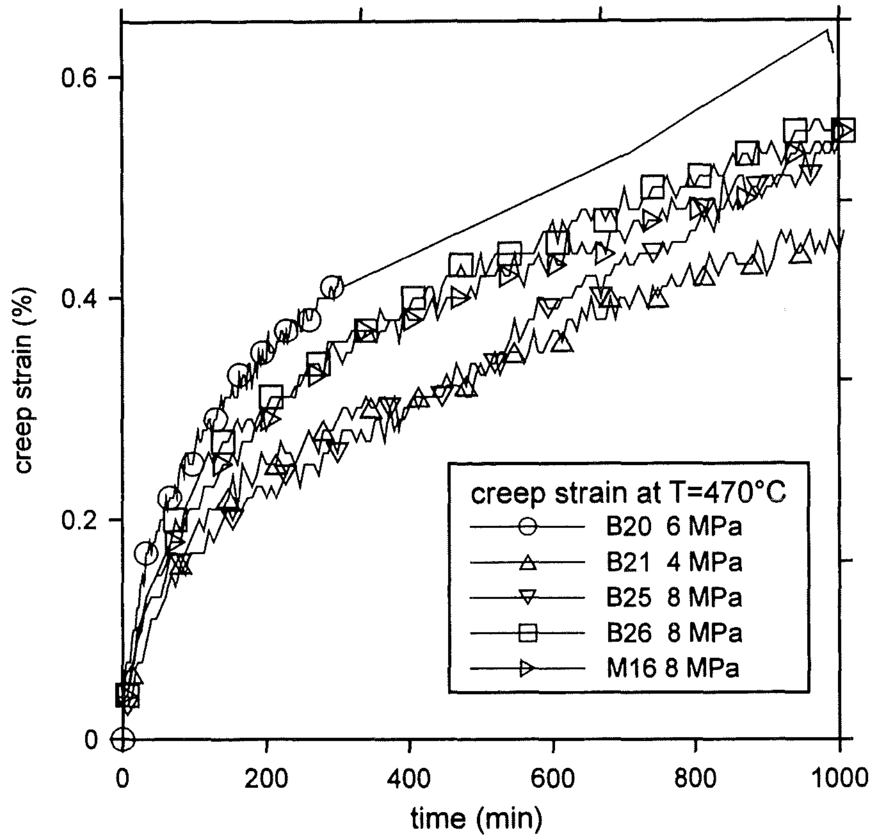

Figure 16. Thermal creep strain at T= 480°C

pronounced [7]). Most of the data are relevant for BBs. From the few MB data, no distinct differences can be seen.

The investigated parameter range is characteristic for the ITER breeding blanket. For this case the effect of thermal creep might be neglected in evaluations of the thermomechanical behaviour of blanket elements. For a DEMO reactor significantly higher temperatures are also of interest. Therefore, the present data might be considered as a first step but further experiments are required at higher temperatures.

3.5. Characterisation of pebble beds after UCTs

After demounting the upper Al2O3 disc the bed surface of the BBs was changed compared to the state after filling: the upper small pebbles had moved downwards by ≈ 1mm indicating that small pebbles had filled some voids in the pebble bed during the experiment. In order to visualise the bed structure a portion of the pebble bed was fixed by glue. It proved that many large pebbles were separated by small pebbles, as also seen in Fig.17. There was a significant hooking of small and large pebbles due to the large surface roughness, see Fig.18.

For BBs it was difficult to detect visually any pebble deformation. For the MBs, a very small portion of the pebbles showed cracks, preferably those pebbles with significant initial surface indentations or inner voids.

The elastic deformation of the pebbles was reduced due to strength hardening.

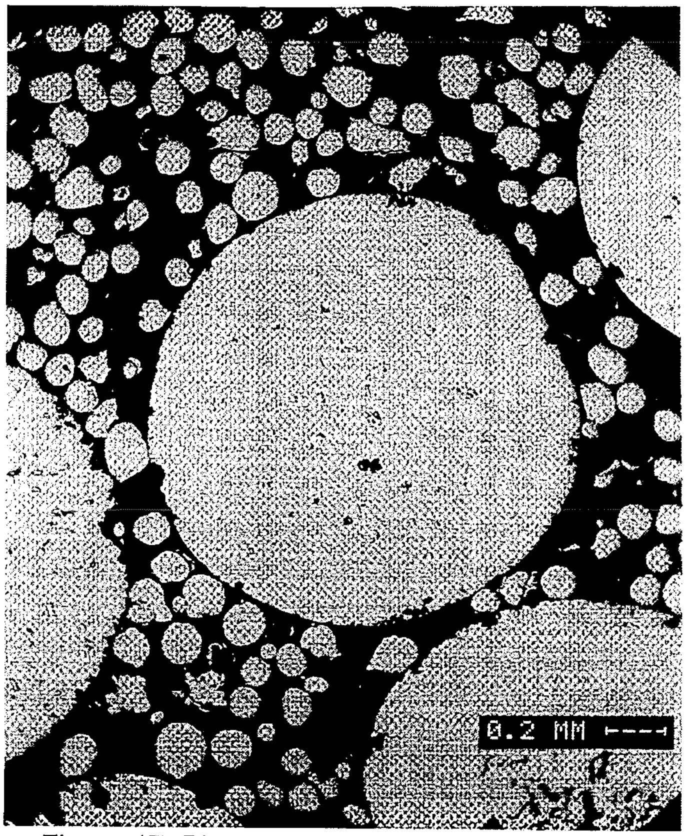

Figure 17. Binary pebble bed after UTC

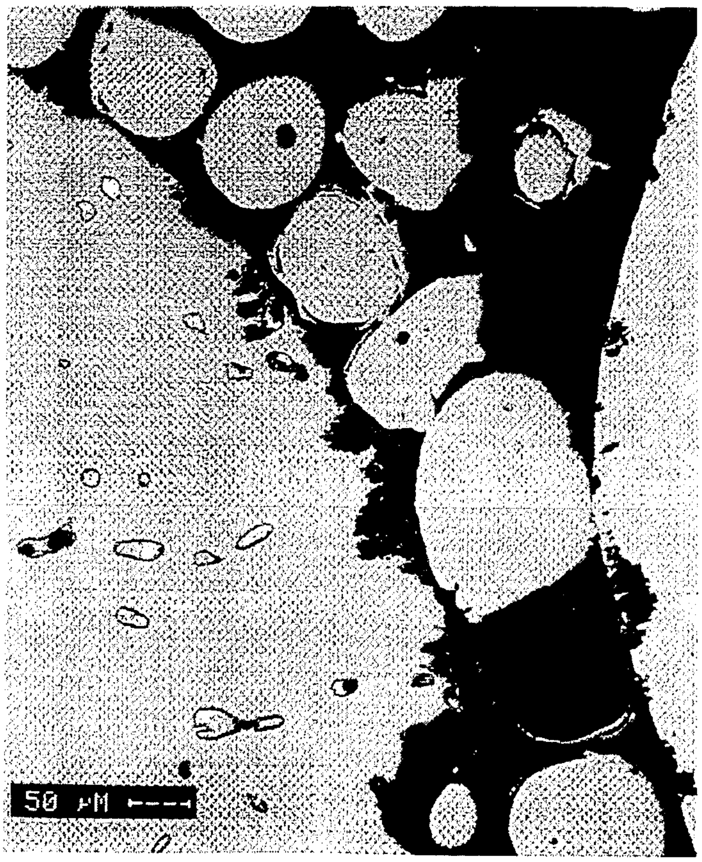

Figure 18. Binary pebble bed (detail of Fig.17) after UTC

4. RESULTS FROM TRIAXIAL COMPRESSION TESTS (TCTs)

In the following, first results from TCTs are reported. Due to experimental difficulties, only a few experiments could be performed up-to-now.

Figure 19 shows a characteristic result of a TCT. Because of the isotropic initial compression of the pebble bed to the value of the selected horizontal pressure p_2, the bed is more compressed at the beginning than that of a UCT. The axial deformations are quite small when the axial stress σ_1 exceeds the horizontal stresses $\sigma_2 = \sigma_3$ (corresponding to the horizontal

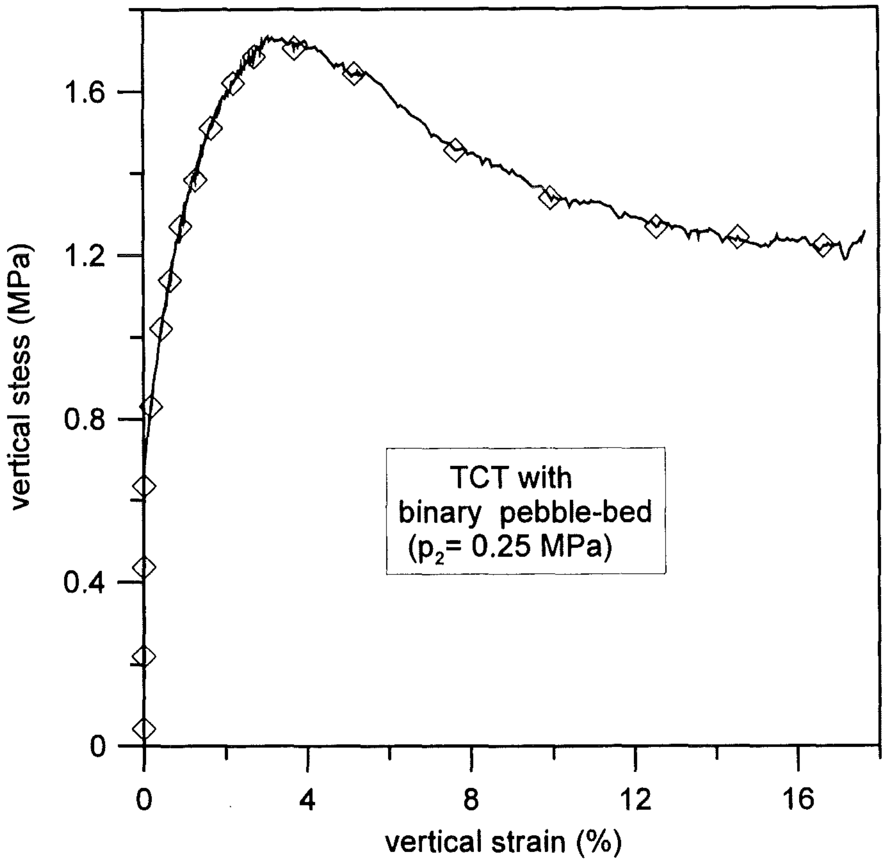

Figure 19. Characteristic result of a TCT

pressure p_2 = 0.25 MPa). In contrast to UCTs, the axial strain becomes increasingly larger with increasing axial stress due to the ability of the pebble bed to deform in the radial direction. The maximum of the curve is reached when no further stress increase is required to generate further strain. This maximum is characteristic for "the state of perfect plasticity" and the internal friction angle α, defined by $\sin\alpha = (\sigma_1-\sigma_2)/(\sigma_1+\sigma_2)$, at this position is of prime importance.

Depending on the initial consolidation of pebble beds, the minimum required stress for further strain increase can be fairly constant or it can become smaller. The latter tendency is clearly observed for the beryllium pebble beds, see also Fig 20.
Figure 20 contains results for p_2 = 0.25 MPa for both MBs and BBs. As ordinate, the deviator $(\sigma_1-\sigma_2)$ is used. The results for BBs are somewhat higher than those for MBs; differences in the curves might be due to different filling factors, see Table 1. Because of the few data points, the influence of the filling factor cannot be separated.

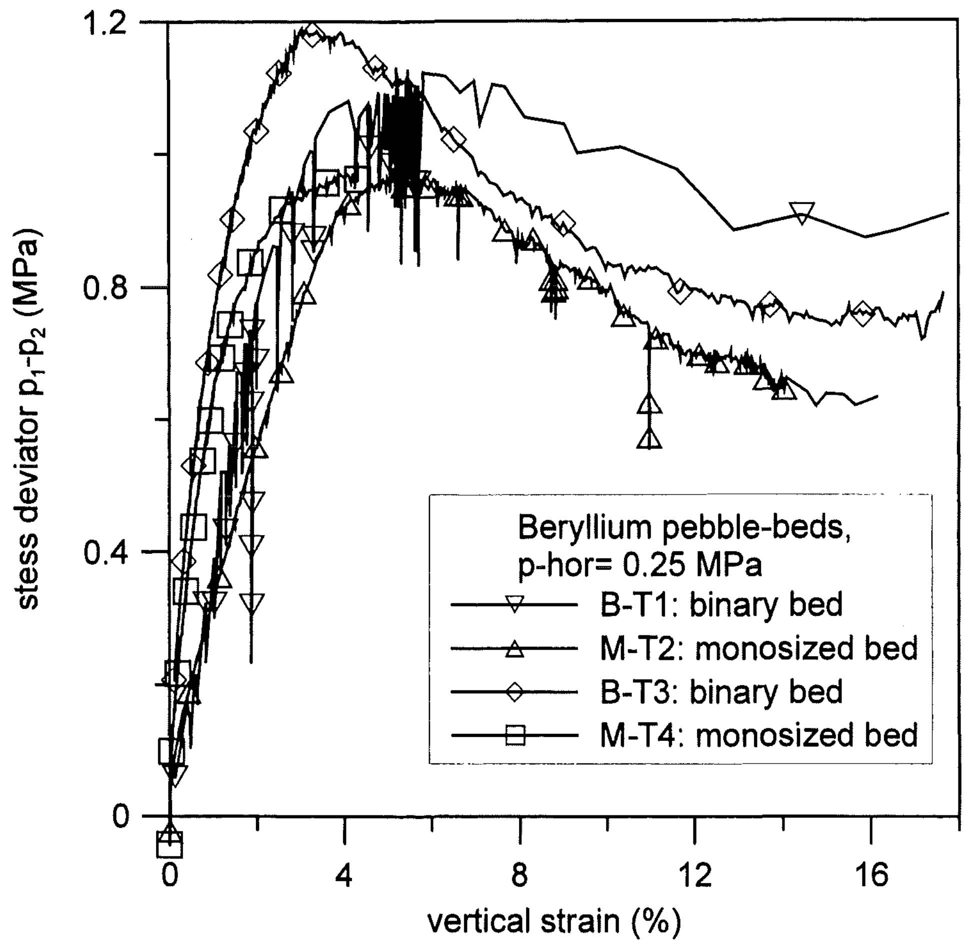

Figure 20. TCTs for MBs and BBs at p_2 = 0.25 MPa

An important result is shown in Fig. 21 where the data at the stress maximum are presented and are compared with results from Li_4SiO_4 and glass pebble beds: The data for the beryllium beds are distinctively higher than those for the other granular materials which consist of fairly spherical pebbles with much smoother smooth surfaces. The slopes of the curves are representative for the inner friction; the higher inner friction of the beryllium beds might be explained by the more irregular pebble shapes and the rougher surfaces.

The inner friction angle is an important quantity for the description of the flow of particles. For blanket relevant shallow Li_4SiO_4 beds (bed height ≈ 10 mm) it was shown experimentally and theoretically[5] that the particle flow becomes negligible at already quite low side stresses (perpendicular to the direction of the axial stress). This facilitates the computation and reduces considerably the experimental effort to characterise pebble beds (UTCs would be sufficient). A higher friction factor of beryllium pebbles compared to Li_4SiO_4 pebbles favours the tendency that a flow of particles is suppressed. Calculations will be performed in the near future if for larger beryllium bed heights (≈ 40 mm) the particle flow is of concern.

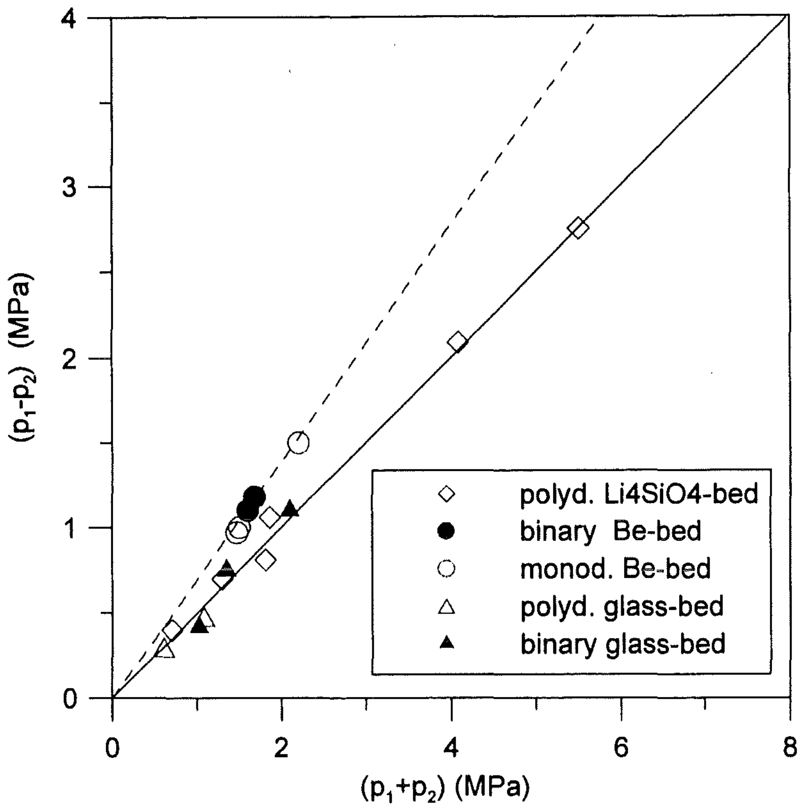

Figure 21. State of perfect plasticity of different granular materials

5. INFLUENCE OF INITIAL STATE OF PEBBLE BEDS

For a given granular material the filling factor γ is an important parameter. For polydisperse Li_4SiO_4 pebble beds, the stress-strain dependences differed significantly for different filling factors [8].

For MBs, maximum filling factors for an ideal face-centered cubic array of spherical particles are $\approx$ 74%. Real beds are not of this array and for small bed dimensions the larger local porosity close to the walls decreases the averaged value. It is generally assumed that the wall influence starts to become remarkable at bed dimensions less than $\approx$ 10 pebble diameters. In practice, values of $\gamma \approx 65$ % are reached for large bed dimensions with smooth particles. For rough particles, the attainable values decrease often to values of less than 60%, see e.g. [2]. In the present experiments (Table I) the values forMBs were between 60 and 62 %.

For BBs, filling factors for the small pebbles of up to 20 % are observed for smooth particles. Again, these values become significantly smaller for rough pebble surfaces.

When preparing dense binary beds consisting of rough pebbles the swim-up effect cannot be avoided totally, see Section 2.5. There are procedures to limit or to undo this effect. However, these procedures generally give rise to a significant internal stress build-up (in experiments with different granular materials a stress build-up of several MPa was observed). This effect, was recently also confirmed for beryllium beds [9]. This internal stress build-up represents a preconsolidation of the bed and has a strong impact on the results of a subsequent UCT.

In order to investigate the influence of the filling factor formonosized and binary beds some screening tests with glass pebbles were performed. The larger pebbles (equivalent diameter about 2 mm) consisted of rounded cylindrical particles with a diameter to height ratio of about one. The small pebbles were spherical with diameters between 0.1 and 0.2 mm. Compared to the beryllium pebbles, the pebble surfaces were very smooth.

The UTCs were performed either with the large pebbles loosely poured in the cylindrical container (nonvibrated case) or with beds afterwards vibrated. The small pebbles were poured in both cases on the surface of the monosized bed without any remarkable vibration. No attempt was made to obtain maximum filling factors but to avoid a swim-up effect. Table 3 shows that high filling factors for the vibrated monosized bed were obtained.

Table 3. Characteristics of glass pebble experiments

	diameter (mm)	density (g/cm^3)
large pebbles	≈ 2	2.44
small pebbles	0.1-0.2	2.5
	filling factor (%)	
	nonvibrated bed	vibrated bed
monosized bed	63.1	67.4
binary bed	63.1+16.8 = 79.9	67.4+13.5 = 80.9

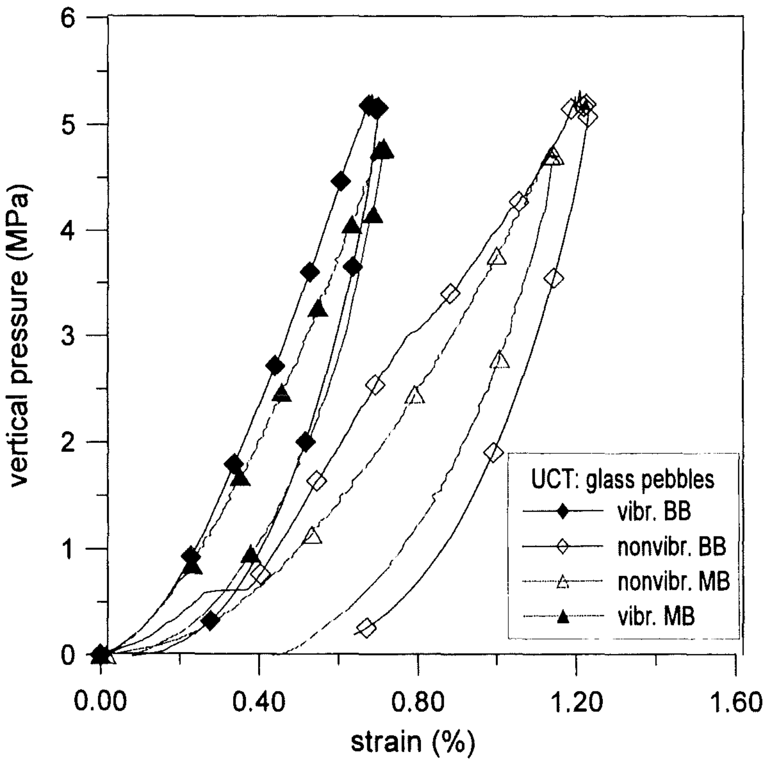

Figure. 22. UTCs with vibrated and nonvibrated glass pebble beds

Figure 22 shows the results: compared to the beryllium beds the curves of the pressure increase are much stiffer and the elasticity during the pressure decrease is more expressed. As expected, the stress-strain dependence is softer for the smaller filling factor of the monosized bed. This difference is quite expressed for a constant strain value. Surprisingly, there is no significant difference between monosized and binary beds. This is in contrast to the present results with beryllium beds where the BBs behave softer than the MBs which might indicate that this difference is caused by the swim-up effect. As already mentioned, the extrapolation of these results to beryllium beds is probably very limited; the TCTs also showed significant differences between binary glass pebble beds and beryllium pebble beds. In experiments [10] with binary beryllium beds in high cylinders (diameter. 0.116 m, height:≈ 0.6 m) a homogeneous distribution of the small pebbles could only be achieved by several procedures including heating-up and cooling-down the bed and adding further small pebbles. This procedure was repeated until there was no longer space for further pebbles to be filled in at the bed top. This filling procedure results in an "initial" state of the pebble bed with the maximum filling factor where practically no space for relocation of particles exists. Therefore, essentially, only elastic and plastic deformations occurred during stress increase which means that the curve of the 1st pressure increase becomes very steep and is comparable to that of the 2nd pressure increase. This filling procedure might be acceptable for the ITER blanket where the restrained strains (which give rise to the stress build-up) are very small. For restrained strains of several %, characteristic for a DEMO blanket, such a high filling factor would result in probably unacceptable stress values.

In the frame of a new test facility to investigate the heat conduction of significantly deformed beryllium pebble beds (HECOP) [11], special experiments were performed with a 100 mm cavity in order to obtain high filling factors using amongst other things an electromagnetic vibrator. The same device was used at the end of the present investigations. Figure 23 shows first results: no significant difference exists for the 100mm container between the MB and BB experiments with very high filling factors (compare Table I). Surprisingly, the results for MBs using different containers does not differ either although the filling factors are very different. In both cases it was attempted to reach high filling factors. Further experiments will be performed in order to determine if the differences in filling factors are caused by the different container diameters.

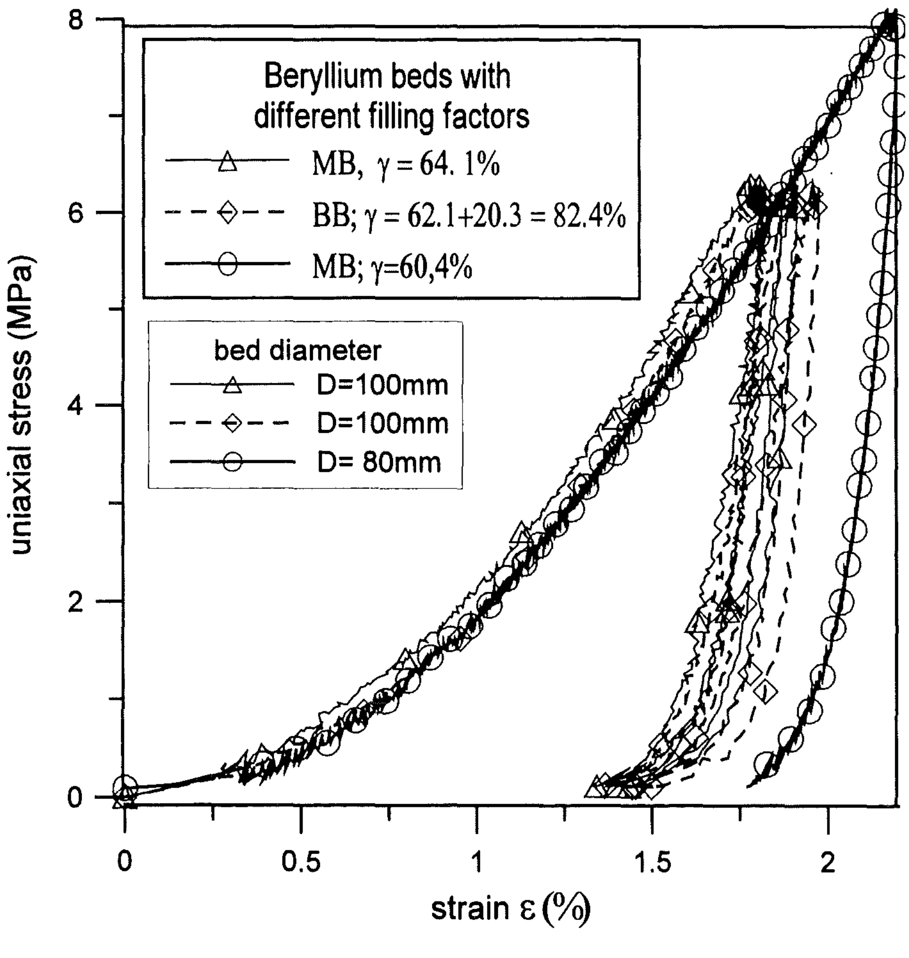

Figure 23 UCTs with high filling factors

6. CONCLUSIONS

Uniaxial compression tests with monosized and binary beryllium pebble beds were performed in a temperature range between ambient temperature and 480 °C and pressures up to 8 MPa. Empirical correlations for the modulus' of deformation are presented for the different bed types and first measurements for thermal creep are presented.

Additionally, results for triaxial compression tests for monosized and binary beds are reported. The internal friction of these beds is significantly larger than that for spherical particles with relatively smooth surfaces (ceramic breeder pebbles) indicating that the ability of beryllium pebbles to flow is more suppressed.

The experiments showed that the initial state of consolidation of the pebble bed is very important for the stress-strain dependence. Therefore, pebble bed characterisation tests (UCTs, TCTs, etc.) and related experiments (e.g. heat conductance investigations) are to be performed with the same initial bed conditions as existing in the blanket. The latter depend on blanket relevant filling procedures which are presently not sufficiently defined and require corresponding investigations. The filling issues are much less expressed for monosized (or polydisperse) beds than for binary beds.

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