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Shear properties of CMB syntactic foam

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In this research, a triaxial shear test is used as a means to provide yield surface data as well as other strength characteristics for carbon microballoon (CMB) syntactic foam. Additionally, pure shear tests and tensile tests are used to probe areas of this stress space not included in the triaxial shear tests. The data are used to characterize the material's yield strength in stress space. The determined yield surface, the strain and other deformational behavior characteristics provide the necessary information for an accurate model and engineering design. The CMB foam specimens were divided into two sets: one with Thornel pitch-based carbon fibers and one without; both use Kerimid 601 as the binder. The CMB syntactic foam with fibers exhibited lower shear strength than the CMB syntactic foam without fibers. This is evident not only in the determined shear envelopes but also in the values obtained for the hydrostatic yield of both foams. Complementary analysis of the blending process of mixing fibers with CMB has been shown to destroy the microballoons and thus reduce the foams strength. The consequences of incorporating alternative materials can be verified with further testing. © *2006 Springer Science + Business Media, Inc.*

1. Introduction

Syntactic foams are composite materials formed by mechanically combining hollow microspheres with resin. Unlike blown foams created by injecting gas into a liquid causing the bubbles to solidify producing foam, these foams are referred to as syntactic because the microspheres are arranged together. Currently metallic syntactic foams are being developed for their light weight and high compressive strength. Studies show that aluminum alloy syntactic foams may have a shear strength that is 3 times as large as aluminum [1]. Other syntactic foams such as the carbon microballoon (CMB) syntactic foams studied here have been incorporated into engineered systems. The two CMB foams of this investigation use Kerimid 601 as the binder. One foam incorporates Thornel pitch-based carbon fibers (CMBT) (6.35-mm in length and 5–20-μm in diameter) in an attempt to improve the strength while the other does not (CMB). The primary purpose of this investigation was to obtain and compare the strength characteristics of CMB and CMBT syntactic foams to determine the consequences of incorporating Thornel carbon fibers into the foam.

In the design of high consequence engineering systems, material properties of the component are a fundamental consideration. The strength and deformation characteristics for the vital components of the system are frequently desired in order to correctly model and design the system before it is implemented. This is of extreme importance for newly developed composite materials. The material characteristics can be determined by employing various

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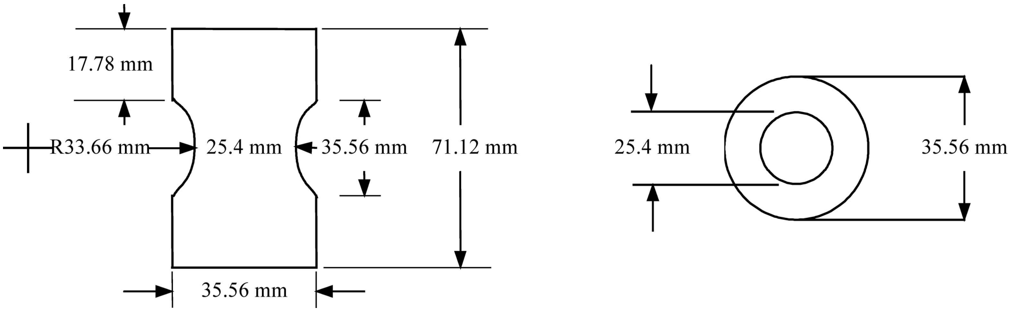

Figure 1 Test Specimen used in the Tensile Test.

tests. However, a great deal of information can be extracted from a relatively simple test such as the triaxial shear test which is extremely useful in providing stress states and their changes over time [2].

In this research, a triaxial shear test is used as a means to provide yield surface data as well as other strength characteristics for the syntactic foams. The data are used to characterize the material's yield strength in stress space, i.e. the behavior of the material when exposed to various stresses. This yield surface is determined by first obtaining the hydrostatic yield stress of the foam followed by various triaxial compression tests with the minor principal stress held constant at different percentages of the determined hydrostatic yield stress. The determined yield surface, the strain and other deformational behavior characteristics provide the necessary information for an accurate model and engineering design.

2. Methodology

In a triaxial shear test, stress is applied axially in three principal directions perpendicular from one another. These stresses are known as the major and two minor principal stresses. Due to the experimental limitations of stress applications, the minor stresses are applied equivalently. The types of compression tests (triaxial shear tests) performed were as follows: uniaxial compression, hydrostatic compression, and several compression tests under a variety of confining pressures while increasing the major principal stress. The tensile test was conducted to determine the average tensile stress present at failure. From that value along with the stress concentration factor, the maximum stress was calculated. These tests were performed on CMB and CMBT foam samples: one set consisting of 16 samples with Thornel fibers and one of 16 samples without fibers. The foam samples were cylinders: 71.12 mm in length and 35.56 mm in diameter. The samples were slightly different for the tensile tests, where an "hour glass" shape 71.12 mm in length, 35.56 mm in diameter at the ends and tapering to 25.4 mm in the middle of the specimen was used as depicted in Fig. 1. The dimensions of the specimen produced a maximum stress at the midpoint of the sample which permitted the calculation of the tensile stress needed to cause failure in the foam [3]. The procedure and apparatus for conducting the pure shear test can be found in ASTM D 5379/D 5379-98 [4].

In the uniaxial compression test, the major principal stress was increased while keeping the minor principal stresses equal to zero. To accomplish this no hydraulic fluid was used in the triaxial compression cell. The major principal stress was increased by moving the base under the triaxial compression cell upwards at a constant rate of about 0.1524 mm/min or a strain rate of about 3.16×10^{-3}/min.

In the hydrostatic compression test an equivalent pressure was applied in all directions by the hydraulic fluid, minor stress equal to major stress. A latex membrane protected the CMB and CMBT foam specimens from the hydraulic fluid. Using the hydraulic hand pump, the pressure within the triaxial compression cell was slowly increased at a constant rate with stops every 172, 345, 689 kPa to equilibrate. The determined hydrostatic yield of the foam was then used to specify the triaxial compression test matrix. The matrix consisted of tests done at confining pressures that were 90%, 65%, 37.5%, and 12% of hydrostatic yield with latitude to include additional tests at various confining pressures.

Each triaxial compression test was performed by first obtaining the confining pressure, minor principal stress, at the desired pressure. This was accomplished through the use of the hydraulic hand pump which was used to slowly increase the hydraulic pressure at a constant rate with stops in intervals of 69, 172 or 345 kPa to equilibrate. Once the desired confining pressure was reached it was held constant while the axial load on the sample was increased at a deformation rate of 0.1524 mm/min, thus increasing the major principal stress to determine the yield at this confining pressure. Fig. 2a and b depict the triaxial testing apparatus used for the triaxial tests.

3. Material characteristics and material properties

The following sections present the properties determined from the triaxial compression, pure shear and tensile tests

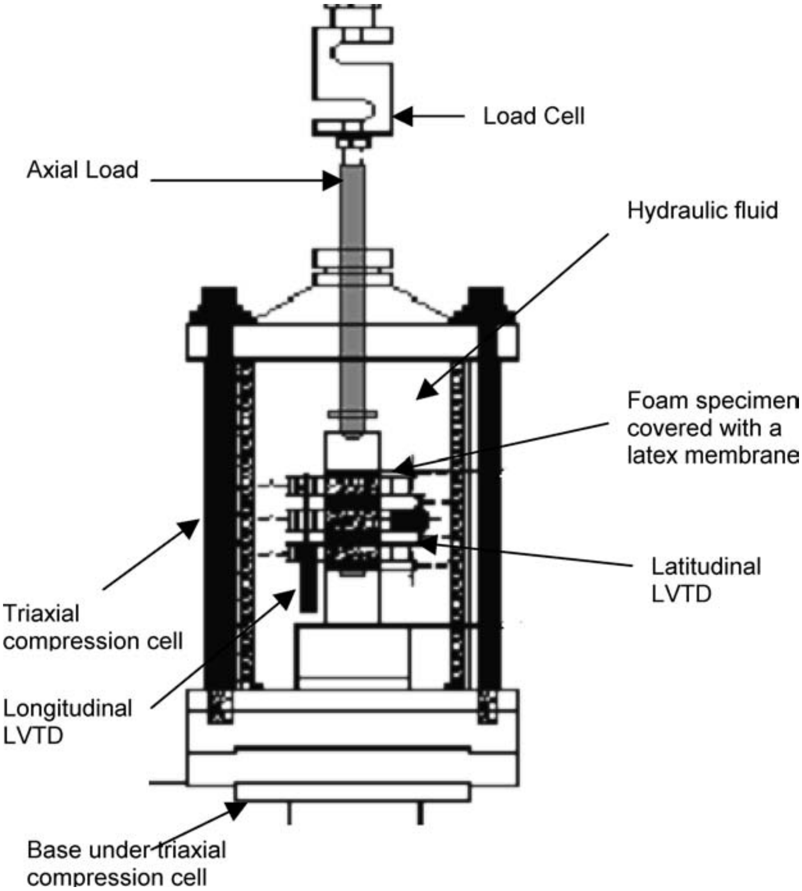

Figure 2a Test Apparatus used in the triaxial test.

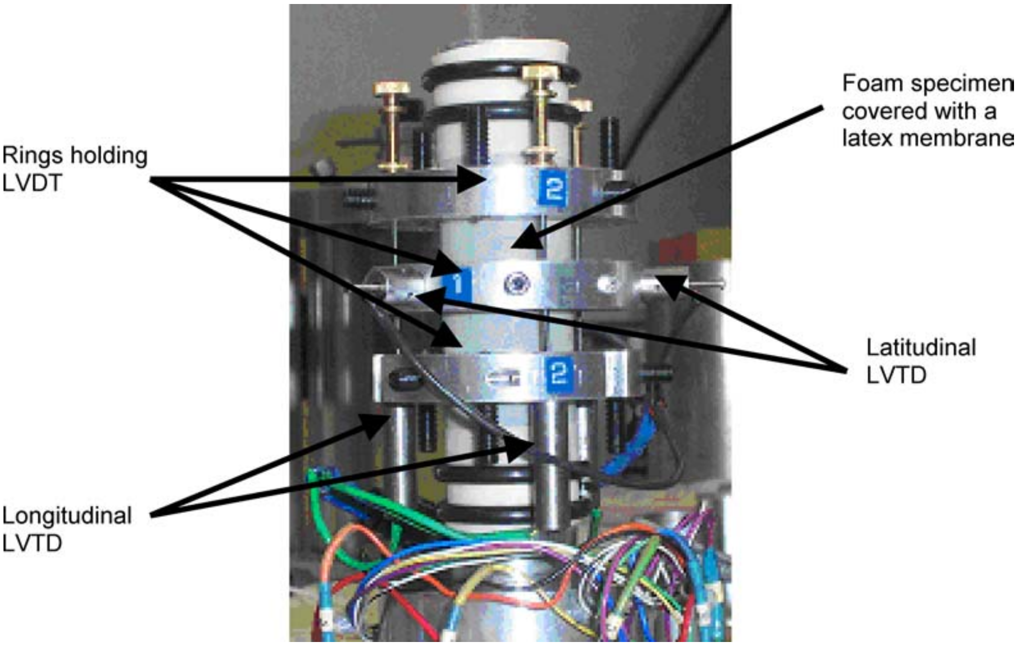

Figure 2b Close-up of the triaxial compression cell showing the foam specimen with latitudinal and longitudinal LVDT and rings.

and briefly describes the equations used to determine these properties. Note that the stress in compression is treated as positive.

3.1. Mechanical properties derived from the triaxial test

The confining pressure, σ_3, applied to the sample was measured with the pressure gage. Subtracting the measured pore pressure, u, within the sample from this value results in the effective minor principal stress, σ_3':

$$\sigma_3' = \sigma_3 - u \tag{1}$$

Three stresses make up the effective major principal stress, namely, the confining pressure, the longitudinal stress applied to the specimen by the load frame (piston), and the pore pressure. Note that pore pressure measurement was for leak detection purposes only; the pore pressure was approximately zero for all tests performed.

$$\sigma_1' = \sigma_3 * \left(1 - \left(\frac{\phi_{\mathrm{PD}}}{\phi_{\mathrm{SD}}}\right)^2\right) + \frac{P}{A_s} - u, \tag{2}$$

where ϕ_{PD} and ϕ_{SD} are the piston diameter and the specimen diameter, respectively.

Contributors to the effective major principal stress are the confining stress and the pressure applied to the specimen by the load frame, where P is the force applied by the load frame piston and A_s is the surface area over which this force acts. The values of the major and minor principal stress are needed to calculate other parameters discussed next. For the hydrostatic compression tests the calculated value of deviatoric stress, q, is zero because in this case $\sigma_1' = \sigma_3'$. For the uniaxial test, $q = \sigma_1'$.

$$q = |(\sigma_1 - \sigma_3)| \tag{3}$$

The mean stress, p, is the average of the three principal stresses applied to the sample. Recall that there are three mutually orthogonal principal directions. Due to the limitations of the triaxial compression tests conducted for this study, the stresses in two of these principal directions are always equal. Thus the effective minor principal stress is given by

$$p = (\sigma_1' + 2(\sigma_3'))/3 \tag{4}$$

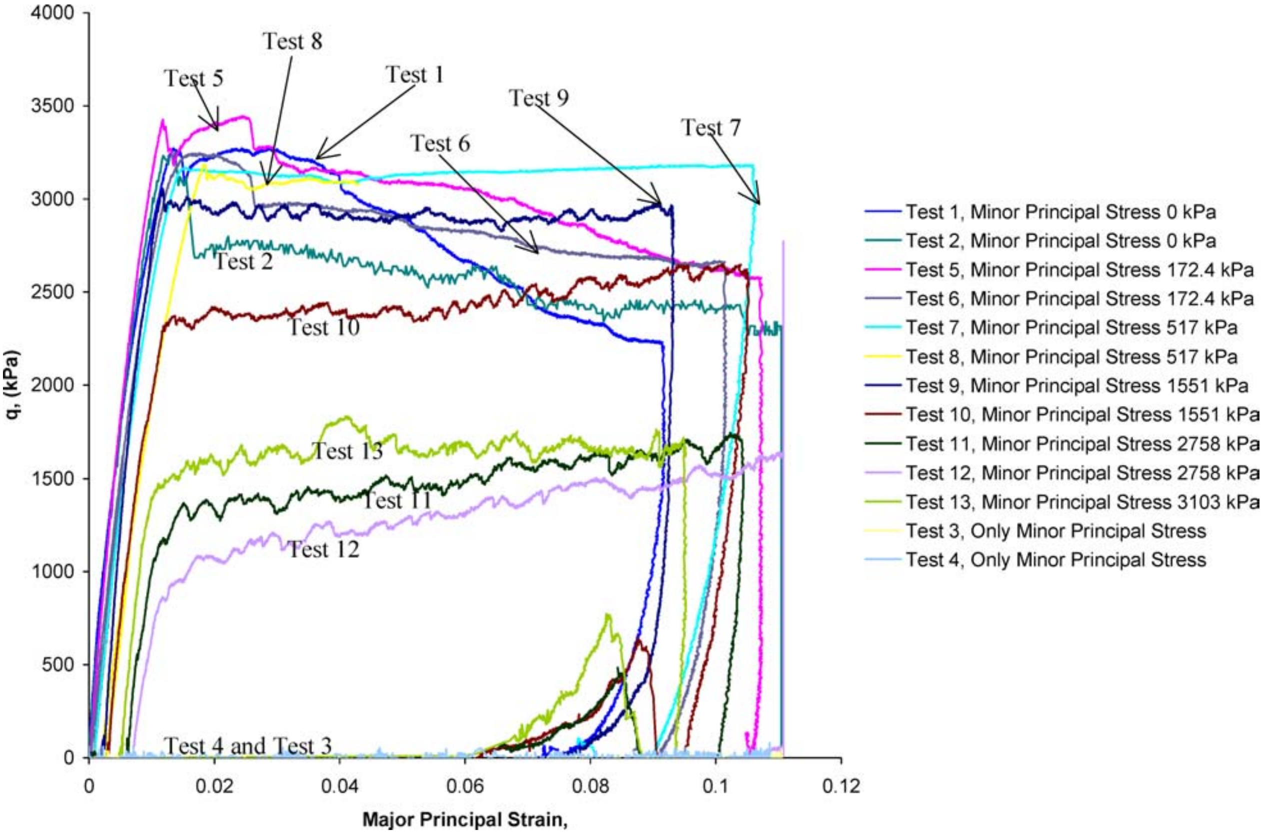

Figure 3 Composite plot of q vs. ε_1 for CMBT. The plot below demonstrates the behavior of the material during the various triaxial tests. In some of these tests the desired minor principal stress was reached and held constant while increasing the major principal stress to yield and beyond. Other tests were conducted by only increasing the minor principal stress to yield and beyond. Each test conducted is labeled.

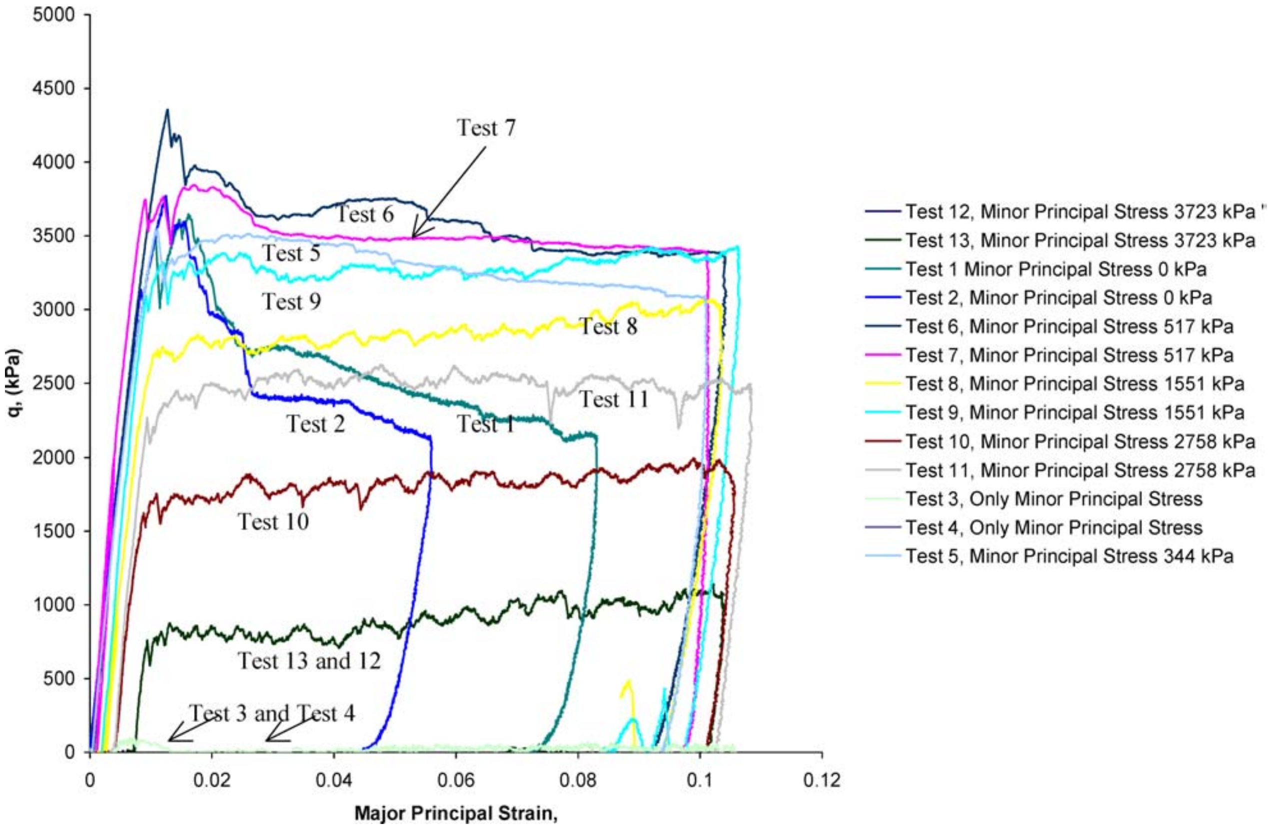

Figure 4 Composite plot of q vs. ε_1 for CMB syntactic foam. Like Fig. 2, the plot below demonstrates the materials behavior at various triaxial tests. The desired minor principal stress was reached and held constant while increasing the major principal stress to yield and beyond. Also, included in the plot below are the results of tests conducted by only increasing the minor principal stress to yield and beyond. Each test conducted is labeled.

Composite plots of p vs. ε_1 (principal strain) for each foam material are found in Figs 3 and 4.

The major principal strain was calculated using a gage length, L_g, of 48.26 mm as.

$$\varepsilon_1 = \frac{-\Delta L_g}{L_g} \tag{5}$$

Three major principal strains were calculated from the deformation values, ΔL_{g}, obtained from the 3 longitudinal Linear Variable Differential Transducers. These strains were then added together and divided by 3 to obtain the average major principal strain.

3.2. Mechanical properties derived from the tensile test

From the tensile test, the maximum weight, W (load), the specimen can support in tension was obtained. Using this determined load along with the area of the specimen midway down the length of the sample A_{m}, the average stress σ_{avg} experienced by the sample at the time of failure was determined:

$$\sigma_{\mathrm{avg}} = \frac{W}{A_{\mathrm{m}}} \tag{6}$$

The maximum stress $\sigma_{\max}$ was then calculated using the determined stress concentration factor K for the dimensions of the prepared specimen [3]. The determined value for K was 1.17 and the maximum stress was calculated by rearranging the following equation and solving for $\sigma_{\max}$.

$$K = \frac{\sigma_{\max}}{\sigma_{\mathrm{avg}}} \tag{7}$$

$$\sigma_{\max} = K * \sigma_{\mathrm{avg}} \tag{8}$$

In order to incorporate this value in p vs. q space, its corresponding values of q and p were calculated using Equations 3 and 4 where $\sigma_{\max} = \sigma_1'$. The values obtained for p will be negative because the stress is tensile rather than compressive and the values for q are positive, see (3). Therefore the maximum stress values obtained from the tensile test will be plotted to the left of vertical q axis. The values obtained from this test are displayed in Table I below.

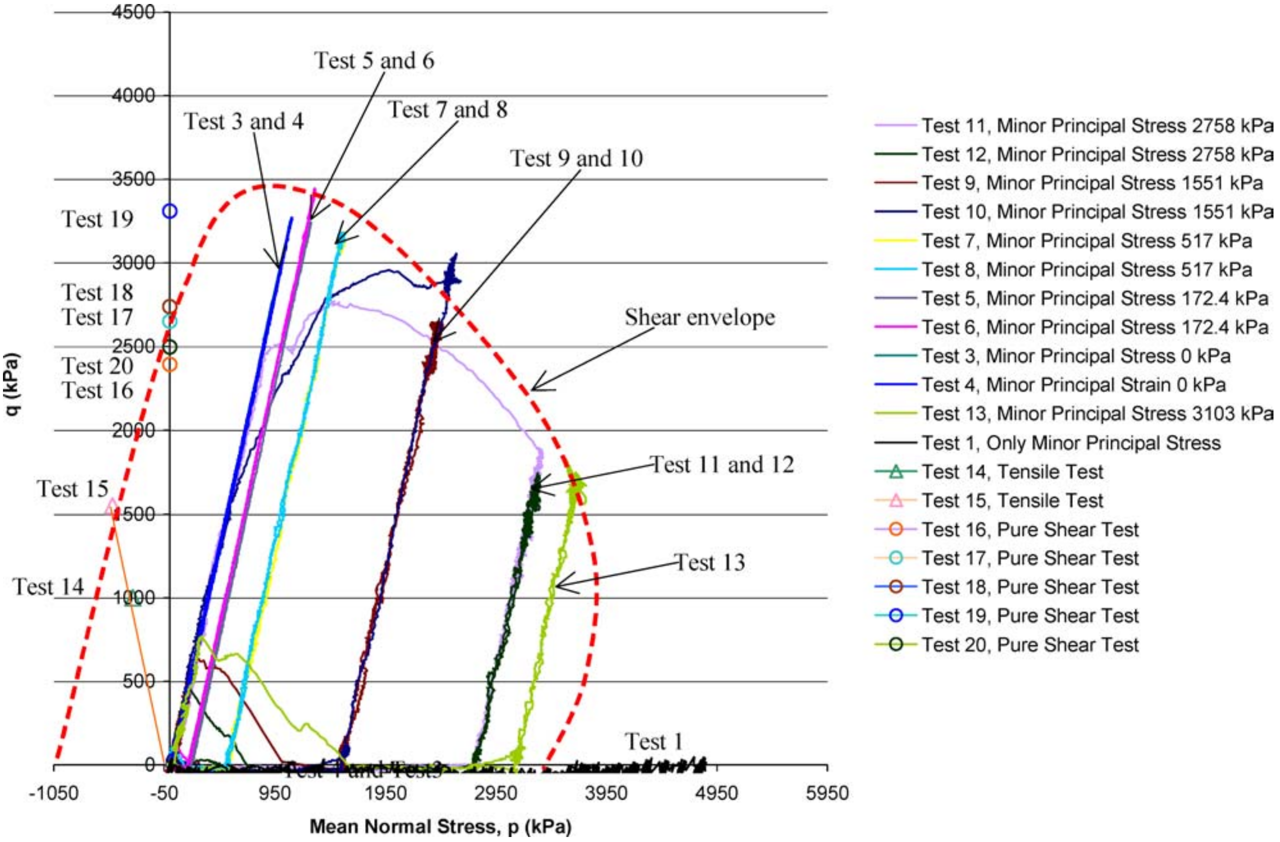

Figure 5 Composite plot of p vs. q for CMBT. Each test is depicted by a different color and the colors are the same used in Fig. 2. An envelope has been drawn, the red dotted line, depicting the maximum shear the material can withstand. Also a line has been drawn from the base to the points at which the material was found to fail under shear loading. Included in this plot are the results of the pure shear test which lie on the vertical axis.

3.3. Mechanical properties derived from the pure shear test

Only CMBT samples were tested in pure shear. From the peak load, P_L, the shear stress τ was determined using the following equation,

$$\tau = \frac{P_L}{H * W_{cr}} \tag{9}$$

where H is the height of the sample and W_{cr} is the cross sectional width. From the shear stress the deviatoric stress was calculated as twice that of the shear stress.

$$q = 2 * \tau \tag{10}$$

TABLE I. Tensile Test Results. These points are used to identify the shear envelopes in Figs 5 and 6 below

Sample ID	Tensile Force (N)	Average Stress (kPa)	Max Stress (kPa)
CMBT	429	848	1000
CMBT	667	1314	1551
CMB	616	1211	1428
CMB	519	1022	1205

The values obtained for q were then plotted in p vs. q space, where the corresponding value of p for each q is zero. Thus the values of deviatoric stress obtained in this test are plotted along the q axis. The values of H, W_{cr}, P_L, τ, q, and the load rate at which the shear tests were run are included in Table II.

3.4. CMB and CMBT mechanical properties and characteristics

The various triaxial compression tests performed provide much useful data to assist in characterizing the foam materials of this study. First and foremost the hydrostatic

TABLE II. Shear test results, q is used to better identify the shear envelope in Fig. 5 below. No pure shear tests were conducted on foam without fibers

Pure shear Tests	1	2	3	4	5
H (mm)	11.47	11.47	11.46	11.49	11.5
W_{cr} (mm)	12.67	12.75	12.78	12.75	12.77
Load Speed (mm/min)	1	1	1	0.1	0.1
Peak Load (N)	173.9	193.8	200.5	242.4	183.3
Shear Stress (MPa)	1.196	1.325	1.369	1.655	1.248
q, deviator stress (MPa)	2.393	2.651	2.737	3.310	2.497

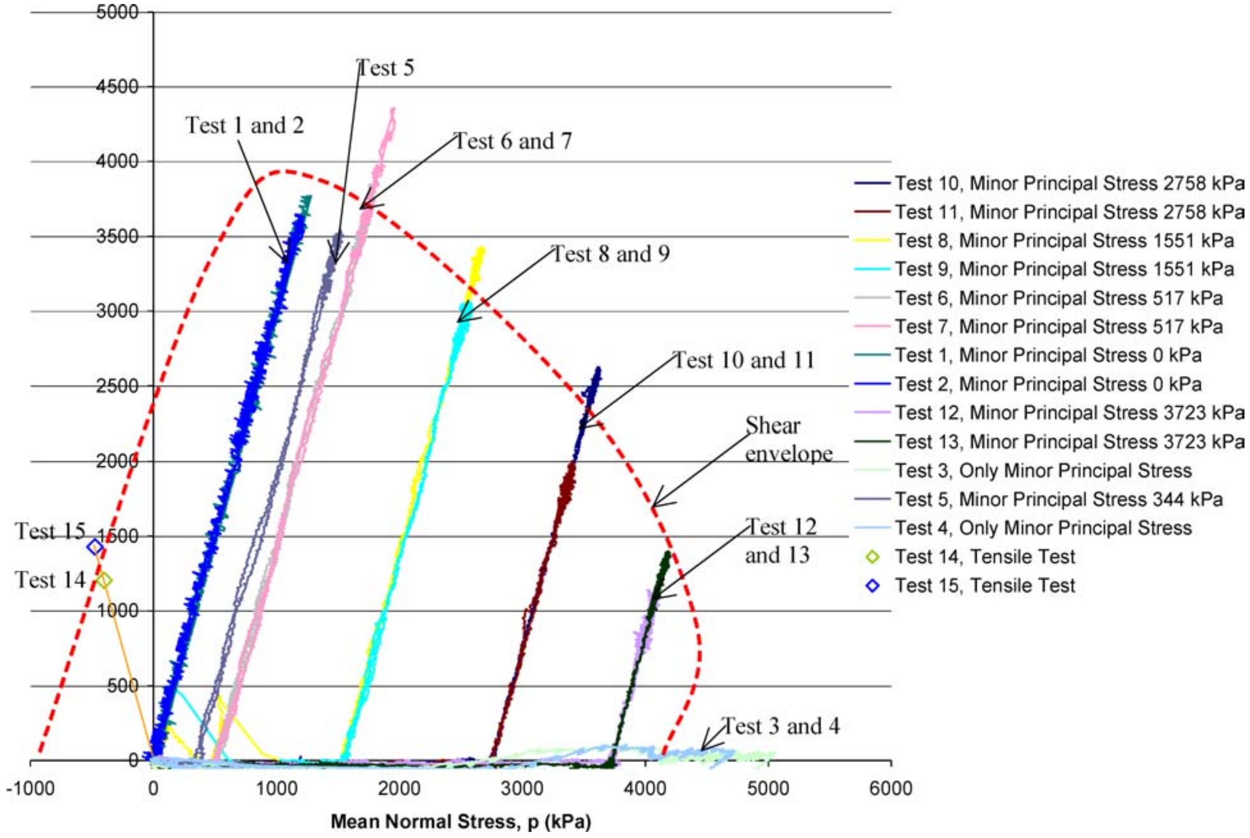

Figure 6 Composite plot of p vs. q for CMB syntactic foam. Each test is depicted by a different color and are the same colors used for the plot in Fig. 3. An envelope has been drawn, the red dotted line, depicting the maximum shear the material can withstand. Also a line has been drawn from the base to the points at which the material was found to fail under shear loading.

test was used to determine the hydrostatic yield for each material. These data are shown in Table III.

From the hydrostatic yield data, a test matrix was laid out for the remaining triaxial compression tests on each foam material as discussed in Section 2. An important relationship resulting from these tests is the relationship between q and ε_1. Plots of shear versus principal strain are presented in Figs 3 and 4. It is important to note that the test matrix was designed to probe stress space thus providing the necessary information to identify the shear envelope in both the CMB and CMBT syntactic foams. The plots of mean stress versus shear for CMB and CMBT syntactic foam with fibers and without fibers along with their shear envelopes are shown in Figs 5 and 6.

TABLE III. Hydrostatic yield from hydrostatic compression tests (kPa). These values were used to determine the test matrix for each sample thus providing evenly spaced tests to probe stress space needed to determine the shear envelopes in Figs 5 and 6

	Test 1, σ_{HY} (kPa)	Test 2, σ_{HY} (kPa)	Test 3, σ_{HY} (kPa)	Average, σ_{HY} (kPa)
CMBT	338	365	331	345
CMB	407	400	N/A	403

4. Conclusions

The CMBT was weaker than the CMB material and exhibited lower shear strength. This was evident in the values obtained from the hydrostatic tests and the determined shear envelopes. The CMB had about 689 kPa higher hydrostatic yield strength than the CMBT. Complementary analysis of the blending process of mixing fibers with CMB has been shown to damage the microballoons accounting for the decrease in shear strength. Since at most only three hydrostatic tests were performed on a given sample, it may be thought that insufficient data were obtained to make this conjecture; however, the data obtained from the hydrostatic compression tests complements the determined shear envelope for CMB and CMBT materials illustrated in the p vs. q plots of Figs 4 and 5. The shear failure envelope for the CMB is somewhat larger than that for the CMBT.

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