CUMING CORPORATION

Technical Note 600-3

NOTES ON THE MECHANICAL PROPERTIES OF SYNTACTIC FOAM FLOTATION AND INSULATION

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1. Efficiency in syntactic foam is achieved through *reinforcement* of hollow spherical fillers by a surrounding matrix of binder resin, resulting in greater hydrostatic strength at lower density than any other known materials system.

2. The sphere is by far the most efficient shape for withstanding hydrostatic (three-dimensional) pressure. However, plain (unreinforced) hollow spheres collapse at a much lower pressure than that predicted by theory, because they have small geometric flaws that result in failure by *elastic buckling.*

3. The reinforcement provided by the surrounding resin prevents the sphere wall from buckling, and forces it to fail in a way much closer to pure compressive stress. This reinforcing effect multiplies the collapse strength of the sphere by a factor that depends on the modulus (stiffness) of the components and the relative size of the spheres.

4. Glass microspheres, which are both very small (100-200 microns) and very stiff (Kgm = 300,000-500,000 psi), are reinforced by a factor of as much as 6x. Fiberglass macrospheres, which are both larger (0.375” avg. dia.) and “softer” (Kep = 30,000-50,000 psi), have smaller factors ranging from 1x to 2x.

5. For example, syntactic foam designed for a riser buoyancy module (cold water only) for service at 5,000 ft (2,220 psi hydrostatic pressure) can be made with K-20-500 glass microspheres and EP-24-1700 macrospheres. The reinforcement factors R at which the two types of spheres will be operating are:

Glass microsphere factor Rgm = 2220/500 = 4.44x
Fiberglass macrosphere factor Rep = 2220/1700 = 1.3x

6. The density (c of the overall syntactic composite will be the sum of the volume fractions times the densities:

$$(c = \underset{\text{macros}}{(0.55)(24.0)} + \underset{\text{micros}}{(0.22)(12.5)} + \underset{\text{epoxy resin}}{(0.23)(70.0)} = 32.05 \text{ pcf}$$

7. And the bulk modulus Kc of the overall syntactic composite can be approxi-mated by the sum of the volume fractions times the relevant moduli:

$$Kc = \underset{\text{macros}}{(0.55)(40{,}000)} + \underset{\text{micros}}{(0.22)(400{,}000)} + \underset{\text{epoxy resin}}{(0.23)(500{,}000)} = 225{,}000 \text{ psi}$$

8. The estimate of bulk modulus Kc of 225,000 psi appears to be a good guess, since one of the “rules of thumb” in designing syntactic foam is to ensure that volumetric compression at service depth is limited to about 1.0%. Compression much greater than 1.0% may begin to crush microspheres and macrospheres.

9. Numerical analysis (see references) confirms that compression approaching 3.0% will usually result in widespread collapse of the rigid spherical fillers. This agrees pretty well with U. S. Navy and ASTM standards which define the *onset* of “hydrostatic crush” as 5.0% displacement loss (i.e., the sum of <u>both</u> compression and loss due to weight gain).

10. It is important to distinguish between volumetric compression and weight gain (water absorption), even though the two are interrelated. Compression has both an *elastic* (recoverable) and a small *inelastic* (non-recoverable) component. Weight gain, which is always <u>non-recoverable</u>, results from intrusion of water into the cellular structure of the foam. A useful approximation of weight gain <u>at rated</u> <u>service pressure</u> can be calculated as follows:

W = Log H, where W = % weight gain
H = number of hours under pressure.

11. Bulk modulus K is the measure of stiffness, or resistance to deformation, under hydrostatic pressure. It is the three-dimensional counterpart to E, the elastic, or Young’s, modulus measuring stiffness under longitudinal (two-dimensional) stress. Both E and K are simple expressions of Hooke’s Law of Proportionality within the elastic limits of the material:

E = S/_, where S = stress, and _ = unit longitudinal strain
K = P/_, where P = pressure, and _ = unit volumetric strain

12. Moduli K and E are related by Poisson’s ratio µ, the ratio of lateral to longi-tudinal strain. Values of µ range from about 0.10 to almost 0.50, depending on the characteristic properties of the material being considered:

K = E / [3(1-2µ)], where both E and K are in psi, and µ is dimensionless.

Value of µ0.100.200.300.400.45K vs. EK = 0.4 EK = 0.5 EK = 0.8 EK = 1.7 EK = 3.3
ETypical mtls.concreteglasssteelleadrubber

13. Numerous experiments and analyses of rigid syntactic foam have resulted in values of Poisson's ratio clustered around µ = 0.333. This is significant because it makes K equal to E. (Shear modulus G = 0.375 E.) Therefore, a good estimate of K for rigid materials can be based on the E of small mechanical samples.

14. These simplifying assumptions do not hold, of course, for flexible materials, which have radically different values of E and K. An elastomeric resin, no matter how flexible in two dimensions, resists three-dimensional deformation about as well as a rigid plastic. And, since the rules of Paragraphs 8 and 9 apply equally to all syntactic foams, it remains necessary for flexible materials to exhibit a bulk modulus roughly 100 times their rated hydrostatic pressure. But it must be noted that elastomers do not provide the reinforcement factors cited in Paragraph 5, so the spherical fillers in flexible systems must be made stronger (and heavier) to withstand the required hydrostatic pressure.

15. The uniaxial compressive strength of a rigid syntactic foam is normally about 75% to 80% of its hydrostatic strength, which means we can make a good esti-mate of compressive strength, based on rated service depth (which in turn is usually 50%-75% of crush depth). Tensile strength, on the other hand, is less related to the strength of the spherical fillers than it is to the integrity of the bond between the spheres and the resin matrix. For this reason, most syntactic foams exhibit relatively low tensile strength, roughly 750 – 1,000 psi. The only way to significantly increase tensile strength is by adding fibers (glass, Kevlar, or carbon) to the syntactic mixture.

16. Armed with the above information, we can estimate the behavior of various kinds of syntactic foam in response to both thermal and bending loads. The ref-erences supply formulas for calculating stresses under a wide range of condi-tions. The following results, for example, were obtained for a tubular sleeve of OD = 10.00" and ID = 6.00", when bent to a uniform radius of 600" (50 ft):

Rigid 5,000 ft-rated syntactic, E = K = 225,000 psi:
Smax = 2,280 psi (should have lots of cracks!)

Flexible 5,000 ft-rated syntactic, E = 0.3 K = 67,500 psi:
Smax = 684 psi (should have no cracks?)

Note: Due to the factors described in Paragraph 15, syntactics will normally fail in tension long before they fail in compression. However, it should be noted that bending and hydrostatic compressive stresses are additive when acting at the same time, and this can in some cases lead to bending failure in compression!

17. A few minutes of “pencil-pushing” leads to the following very general con-clusions about syntactic foam thermal insulation:

The cast-on-pipe method may be prone to cracking in any *very rigid* syn-tactic foam, if significant flexure is involved. The question of whether cracks are thermally “good” or “bad” depends upon the specifics of the application.

A relatively high degree of flexibility ($\mu = 0.4$ or greater) is required to avoid cracking. This degree of flexibility has been successfully achieved with several different high-strength semi-rigid epoxy *C-THERM* materials.

Even flexible (elastomeric) materials contribute significant stiffness, are limited in the amount of bending they can sustain, and may exhibit cracks, especially after thermal aging. Therefore, careful mechanical design is always necessary to achieve an effective system.

18. It is also possible to make some educated guesses about the effects of tem-perature on syntactic foam for insulation applications. For example, returning to the analysis of Paragraph 7, and assuming that raising the temperature of the same material from 4oC to 75oC reduces modulus E of the plastic resin by 50%, yields the following:

$$Kc = (0.55)(20{,}000) + (0.22)(400{,}000) + (0.23)(250{,}000) = 151{,}000 \text{ psi}$$

19. The above result, in effect, “de-rates” the example syntactic foam by about 33%. This agrees with our experience on the *King* project. Additional factors to be considered include possible hydrolysis and the effects of thermal aging, both of which hinge on the chemical properties of the formula. It is possible to obtain this kind of data fairly easily on small samples and then use the information to estimate the mechanical properties required for any kind of service.

20. The purpose of all of this is to illustrate how knowledge of the mechanical properties of syntactic foam can be used to conceptualize materials systems for both “cold” and “hot” water conditions. Naturally, mechanical behavior must be combined with sound chemistry and verified by thorough testing. Using these concepts, we are able to identify the most promising materials, design effective test programs, and move more efficiently toward properties optimized for specific applications.

Glossary

G = Shear (torsional) modulus, psi
K = Bulk (three-dimensional) modulus, psi
E = Elastic (two-dimensional) modulus, psi
R = Reinforcement factor, dimensionless
(= Density, pcf
W = Weight gain, %

H = No. of hours under pressure
S = Stress, psi
P = Pressure, psi
_ = Unit strain, in/in
_ = Unit strain, in3/in3
µ = Poisson's ratio

References

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