Improvement of Fracturing for Gas Shales

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Topical Progress Report

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Executive Summary

As the global demand for energy rises and the discovery of new hydrocarbon resources drops, the recovery from unconventional resources like shale gas become increasingly important. The goal of this proposal is to develop non-damaging fracturing fluids and proppants for gas shale reservoirs that also minimize water use and disposal. We have completed Task 4: proppant mechanical properties. Sphericity, size distribution, bulk density, mechanical properties and chemical compatibility were measured for three lightweight proppants (ULW-1, ULW-2 and ULW-3 supplied by BJ services). ULW-1 is spherical, ULW-2 is slightly angular and ULW-3 is highly angular. Bulk density of ULW-1 is the least (0.6 gm/ml); that of ULW-3 is the highest (1.2 gm/ml). ULW-2 pack has an intermediate density (0.8 gm/ml). Of the three proppants tested, ULW-1 is the most deformable and ULW-3 is the most brittle. ULW-2 is fairly deformable. ULW-1 and ULW-2 lose small amounts of proppants due to crushing of the proppant pack, whereas ULW-3 loses a significant amount due to formation of fines. After failure, ULW-3 leaves fine broken pieces, which can plug up the pores on the fracture surface. All the proppant packs are significantly strong to endure the stresses expected in Barnett shale. Conductivity of these packs must be measured before they can be recommended for high stress fractures.

Introduction

The Barnett shale, since its discovery, is being produced from more than 8,000 wells today (Wang 2008). The success of gas production from Barnett can be attributed to horizontal drilling and hydraulic fracture stimulation. But there were many lessons learned while exploiting Barnett shale gas reserves. Fracture stimulation in shale gas reserves is not the same as fracturing typical gas reservoirs. These shale gas formations have permeability of the order of 10^{-9} Darcies. Therefore, hydraulic fractures need to be thin and long to maximize reservoir contact.

If conventional proppants, like Ottawa sand (specific gravity = 2.65), are used in typical fracturing fluid like slick water, proppants settle during the fracturing process before reaching the end of the long fractures, due to which a lot of producible surface area is lost after stimulation. Re-stimulation is an option, but it makes the process more expensive. The fracturing fluids can carry the conventionally used heavy proppants if they are made more viscous by using polymers in them. This viscosity can be further increased by cross-linking these polymers. However, when the fracturing fluid is very viscous, the resulting fractures are short and thick, and do not reach a major part of the producible area. Also, the large polymer molecules can plug the fracture faces of these extremely low permeability shales.

One way to overcome these problems is to use light weight proppants which can be transported by a less complex fracturing fluid and at the same time, be strong enough to withstand reservoir stresses. These light weight proppants can be used with simpler fracturing fluids, like slick water, effectively. Typical fracturing processes are extremely water intensive. Once the fracturing job is over, there are other issues with the disposal of the fracturing fluids. The proppants being light also gives us an option of using fracturing foams (mixture of gas and liquid phase), thereby reducing the usage of water.

This work focuses on three ultra light weight proppants, ULW-1 (polymeric), ULW-2 (resin coated and impregnated ground walnut hull) and ULW-3 (resin coated ceramic), supplied by BJ services. There are seven laboratory tasks: proppant properties, flow capacity, foam formulation, fracturing data, fracture design, field test and evaluation. We have worked on the first three tasks in the last 6 months. The first task of proppant properties is completed and is described in this report.

Approach

Measurement of Physical Properties of Proppants

Sphericity: Two-dimensional close up images were taken of several proppant particles of each kind and the definition of Riley's sphericity was applied to calculate sphericity. The average of ten readings for all the three proppants was taken as a representative of their kinds. The Riley sphericity (Ψ_R) is defined by,

$$\Psi_R = (D_i/D_c)^{0.5}. \quad (1)$$

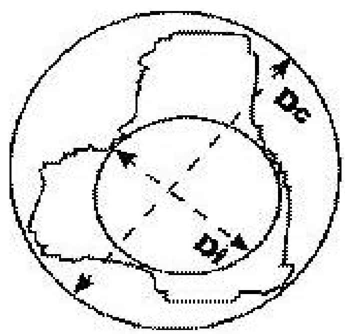

Fig. 1. Riley's sphericity definition

A value of $\Psi_R = 1$ indicates completely spherical and a value of $\Psi_R < 0.6$ indicates extreme angularity.

Size Distribution: This data was provided to us by the supplier, namely BJ services.

Density: The specific gravities of the individual proppants were made available to us by BJ services. We obtained the bulk density of these proppant packs under no confining stress which also gave us the porosity of the pack under no confining stress. Proppants of each kind were simply poured into test tubes. These test tubes were weighed and the bulk volume of the proppants was measured. These values were used for calculation of bulk density.

Assessment of Mechanical Behavior

To assess the mechanical behavior, we performed a strength test in a Humboldt material testing machine. The test tool has three components. A base, a cap and a cylinder surrounding the extended portions of the base and cap. The proppant particle/pack is placed between the extended portions of the base and the cap, where it is tested for its strength.

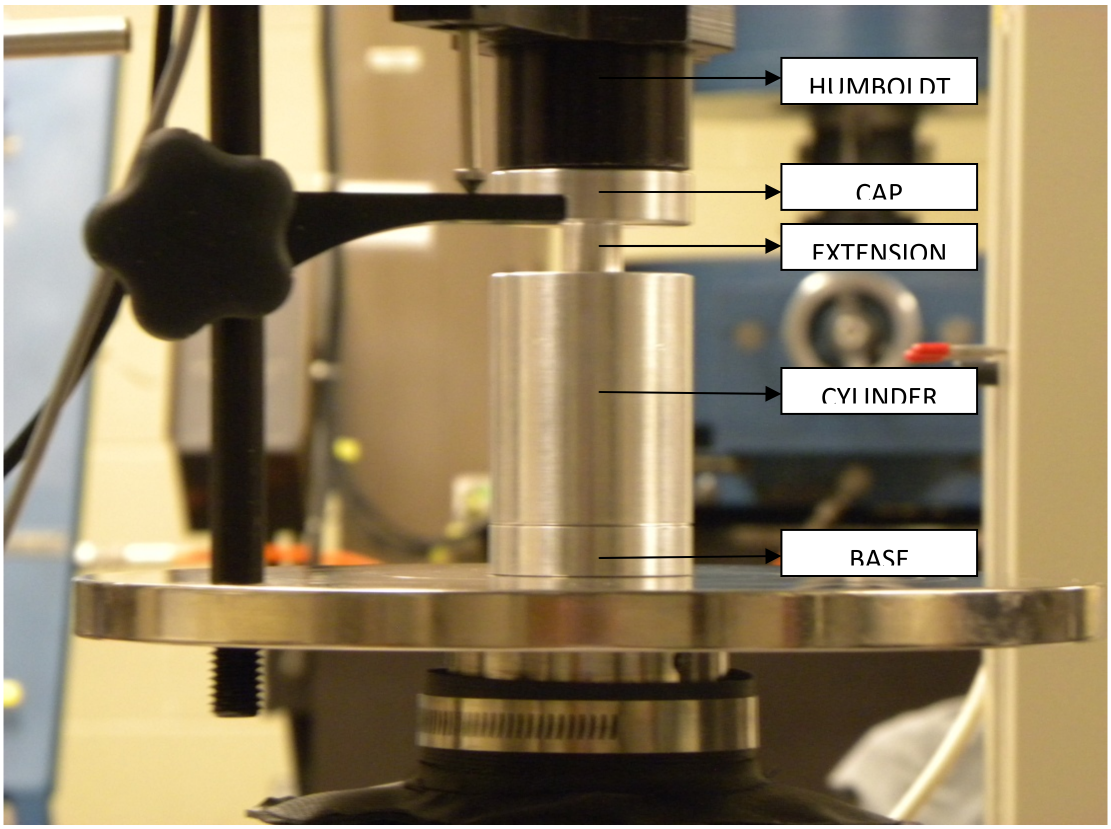

Fig. 2. Image of the strength test tool placed on the HUMBOLDT MASTER LOADER-3000

The tests were performed on several proppants of each kind at room temperature and also at an elevated temperature encountered in Barnett shale. Some of the typical properties of the Barnett shale are listed in the following:

Depth: 5000-8000 ft

Thickness: 100-500 ft

Gas content: 100-300 scf/ton

Reservoir Pressure Gradient: 0.52 psi/ft

Minimum Horizontal Stress: 1365-2184 psi

Maximum possible values for Horizontal Stress: 2357-3771 psi

Average Temperature: 90^{o} C

Proppant Pack Strength Test and Fines Formation: A 5 mm high pack of each proppant was tested for its strength. The aim of this test was to test the compressive strength of proppant packs to increasing stress and also the amount of proppants lost due to the formation of finer particles.

Crush Strength: Crush strength is defined as the load at the failure point in the load versus deformation test. This strength is one of the factors considered in the choice of proppants for a particular shale. This test was done at room temperature and at 90^{o} C which allowed us to compare the behavior of proppants at different temperatures.

Deformability: The measurement of the average value of Young's modulus before failure in effective stress versus effective strain test gave us a tool to assess the deformability of individual proppants. Also, the shape of the particles after the test was carefully examined which qualitatively showed the deformable/brittle nature of particles. The variation in temperature in our tests indicated the change in the deformability of the proppants with increasing temperature, which was visible in the load versus deformation test.

Compatibility of Proppants: The proppants were soaked in water and surfactant-water solutions. Their appearance was checked.

Results and Discussion

Physical Properties

	ULW-1	ULW-2	ULW-3
Average	**1**	**0.67**	**0.82**
Maximum	**1**	**0.76**	**0.94**
Minimum	**1**	**0.53**	**0.67**

Table 1. Comparison of Riley's sphericity for the three proppants tested

Sphericity: ULW-1, a polymeric proppant, was uniformly spherical to the naked eye and this sphericity was reflected in the ten particles tested. The average value for Ψ_R came out to be one with zero standard deviation. The average spericity is listed in Table 1 for the three proppants. Given below is a two-dimensional image for a ULW-1 particle which was used for sphericity evaluation.

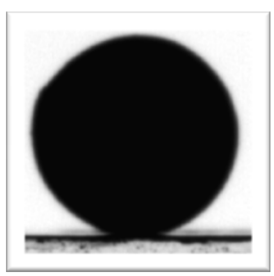

Fig. 3. Image of an ULW-1 proppant

ULW-2, which is a ground walnut hull coated/impregnated by a resin, was angular. For the ten particles tested, the average value for Ψ_R came out to be 0.62 with a maximum value of 0.69 and a minimum value of 0.49.

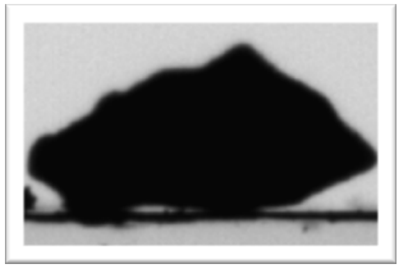

Fig. 4. Image of an ULW-2 proppant

ULW-3, a ceramic proppant, gave an intermediate value for sphericity, i.e., Ψ_R=0.78$\pm$0.11. The distribution of sphericity is shown in Fig. 6.

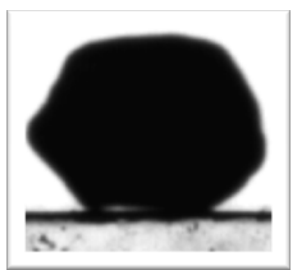

Fig. 5. Image of an ULW-3 proppant

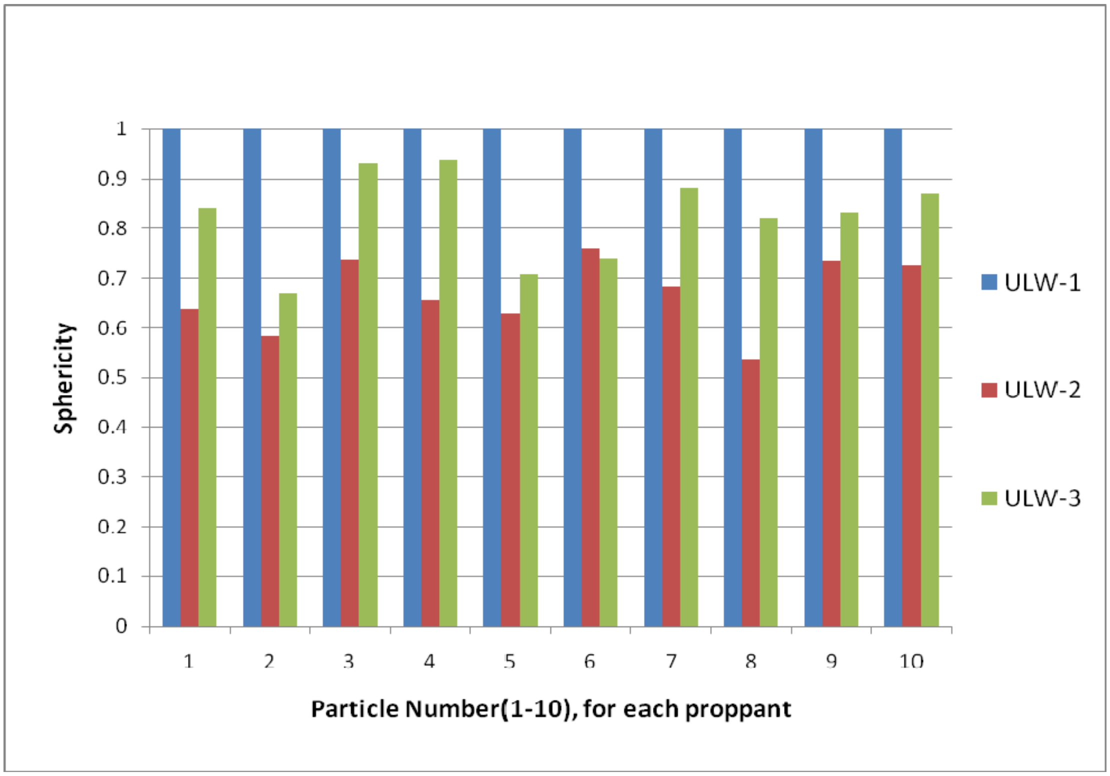

Fig. 6. Comparison of Riley's sphericity for ten particles of each proppant

Size Distribution: The size distribution of each proppant tested was determined by sieve analysis and was made available to us by the supplier. The size distributions are shown in Fig. 7. ULW-1 has a sieve size of 14-40 and the distribution is the broadest of the three proppants tested. ULW-2 has a sieve size of 14-30. ULW-3 has a sieve size of 20-35, the narrowest.

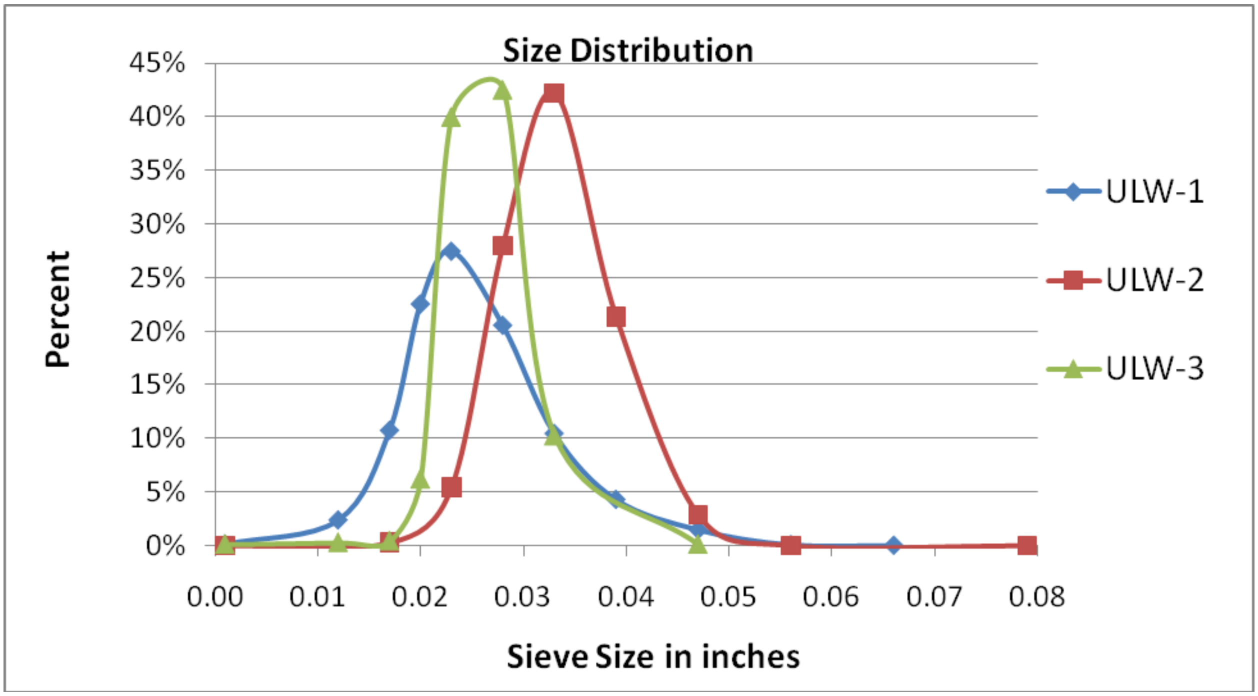

Fig. 7. Sieve size distribution

Bulk Density: The specific gravities of the individual proppant particles were provided to us by the supplier. In this study, we were interested in finding out the bulk density and the respective porosity of the proppant pack of the individual ULW's under no confining stress. This porosity would be compared to the porosity of the proppant pack under closure stress, when we conduct flow capacity tests in the future. The bulk density and porosities are listed in Table 2. Note that with increasing specific gravity, the bulk density increases and the corresponding porosity decreases.

	ULW-1	**ULW-2**	**ULW-3**
Specific Gravity	**1.08**	**1.25**	**1.75**
Bulk Density (g/cc) **(without any closure stress)**	**0.6**	**0.8**	**1.2**

Porosity of Pack (without any closure stress)	**44 %**	**36 %**	**31%**

Table 2. Bulk Density and Porosity Measurements

Compatibility of Proppants: The proppants were soaked in water (for about a month) and surfactant-water solutions (for about a week). Their appearance did not change. It appears that the proppants are compatible with the fracturing fluids.

Mechanical Behavior

Minimum Horizontal Stress: The stresses which the proppants endure in the fractures are the effective minimum stress, which usually is in the horizontal direction. The absolute vertical stress, σ_v is given by

$$\sigma_v = (1.1 \text{ psi/ft})\, h, \text{ where 'h' is the depth in feet.} \quad (2)$$

The effective vertical stress, σ_v' is given by

$$\sigma_v' = \sigma_v - \alpha\, p, \quad (3)$$

where α is Biot's poroelastic constant and has a value of 0.7 for hydrocarbon bearing formations[1] and p is the pore pressure. The effective minimum horizontal stress, σ_H' is given by

$$\sigma_H' = (\nu / (1-\nu))\, \sigma_v', \quad (4)$$

where ν is the Poisson's ratio, and has been assigned an average value of 0.3 for this study. This value might be different for different formations. We will focus our attention on maximum possible value for minimum horizontal stress, which the proppants are expected to endure when the reservoir is completely depleted. These values range from around 2400 psi to 6600 psi, and have been plotted in Fig. 8 for the gas plays in discussion. The figure also supports the idea, that, “No two shale gas plays are alike”. In this study, we focus on application of ultra light weight proppants in Barnett shale at about 90 ^{o}C.

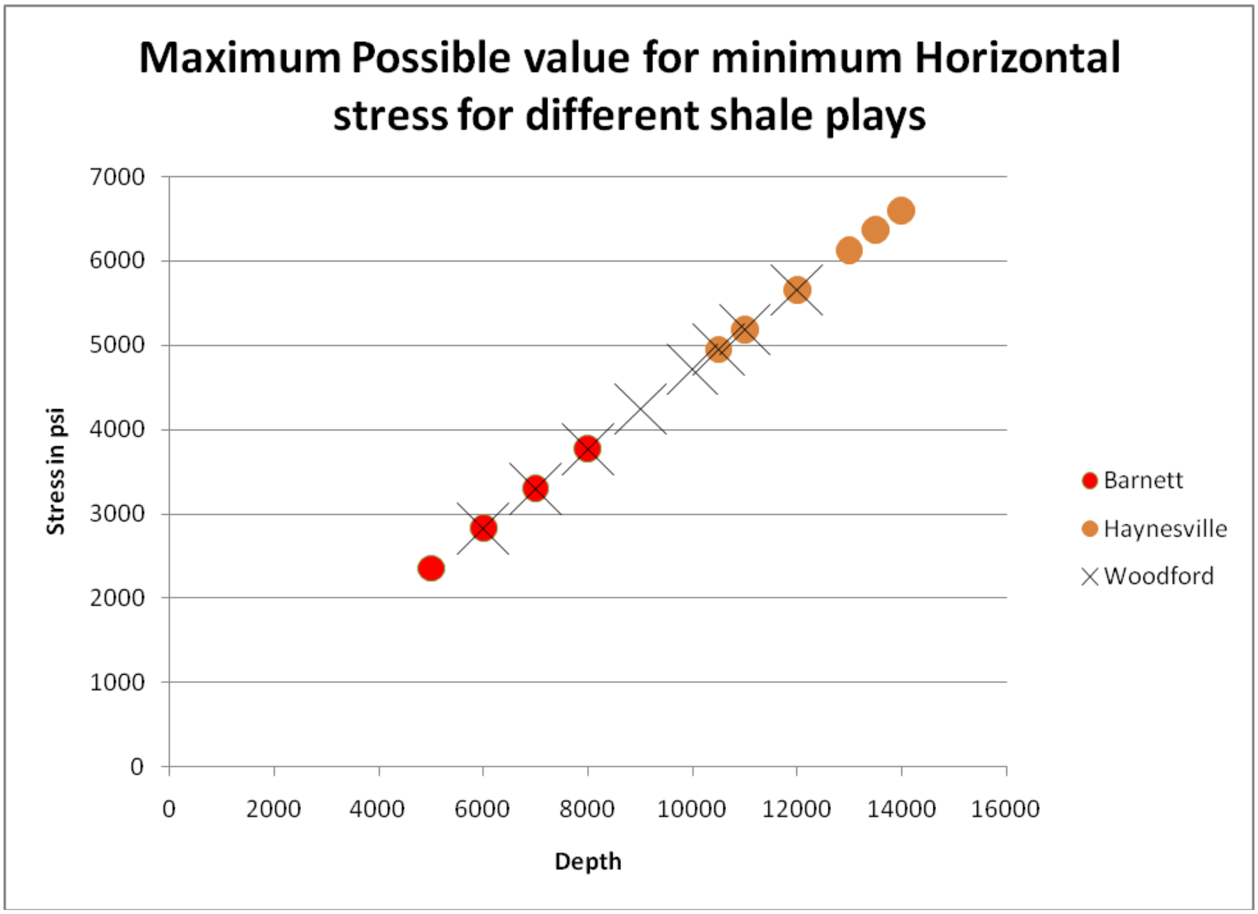

Fig. 8. Maximum Possible values for minimum horizontal stresses for different shale gas plays

Proppant Pack Stress Test and Fines Formation: Stress test was conducted on 1ml (bulk volume) pack of each proppant, simulating a proppant pack between fracture faces. The aim of this test was to study the strength of a pack as well as the formation of finer particles as a result of crushing. Figs. 9-11 show the stress-strain for the three proppant packs. It is to be noted that a high failure stress of a proppant pack alone does not necessarily mean its applicability to a formation with lower stress. This is because, even if the proppant pack does not really get crushed on application of typical reservoir stresses, the proppants in the pack might deform making the whole pack almost impermeable. Again, the conductivity of proppants would be evaluated in future. The failure stress for ULW1 proppant pack is about 40,000 psi (Fig. 9). The amount of fines created at the end of the experiment is also reported in the figure captions and they are small (<5 %). ULW2 pack shows (Fig. 10) a behavior similar to that of ULW1. ULW3 shows a similar failure stress (Fig. 11), but much higher fines formation. The blue band shown in each figure is the expected total stress in Barnett shale formation. The failure stress of proppant packs for each proppant was significantly higher than the stresses encountered in any shale formation.

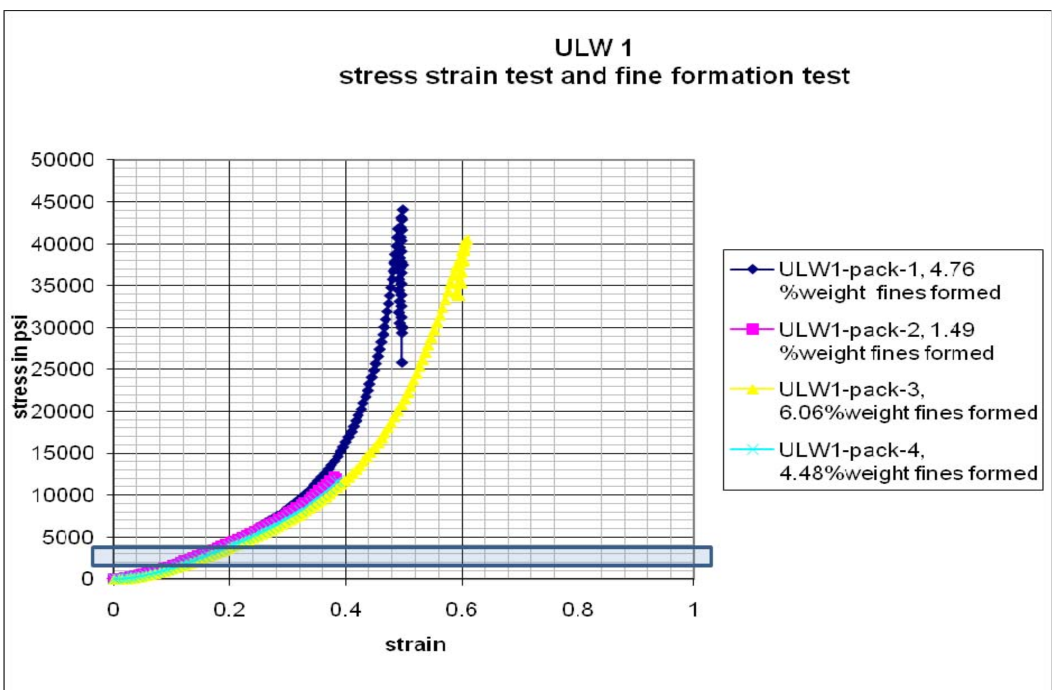

Fig. 9. Deformation of ULW-1 proppant pack at room temperature

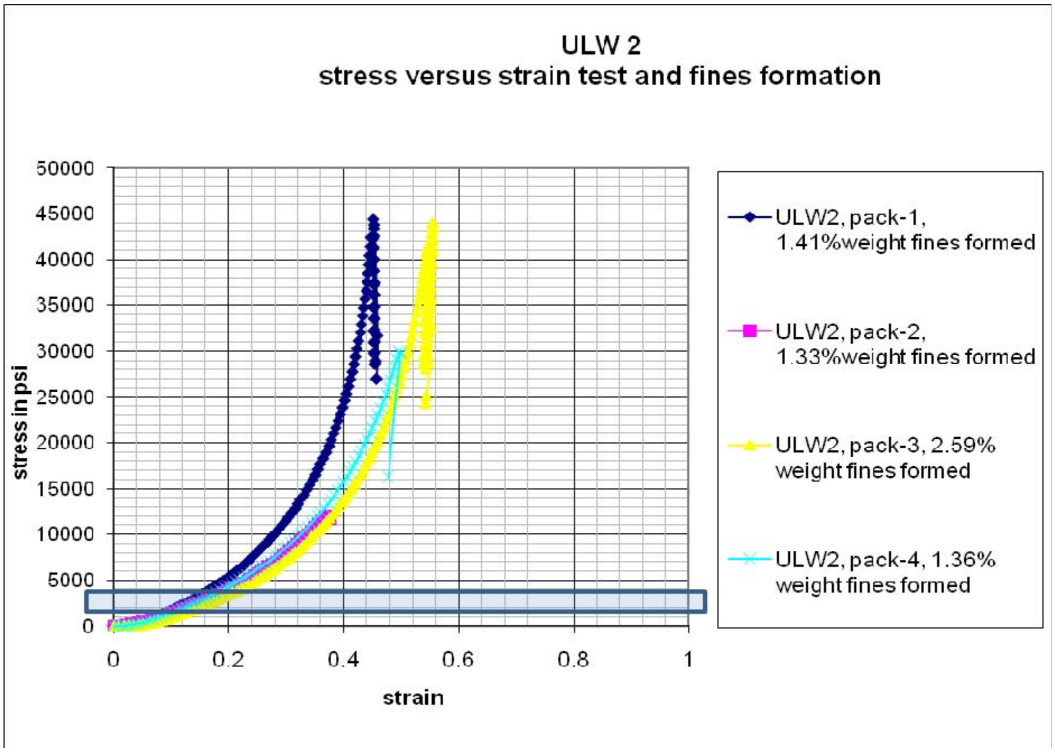

Fig. 10. Deformation of ULW-2 proppant pack at room temperature

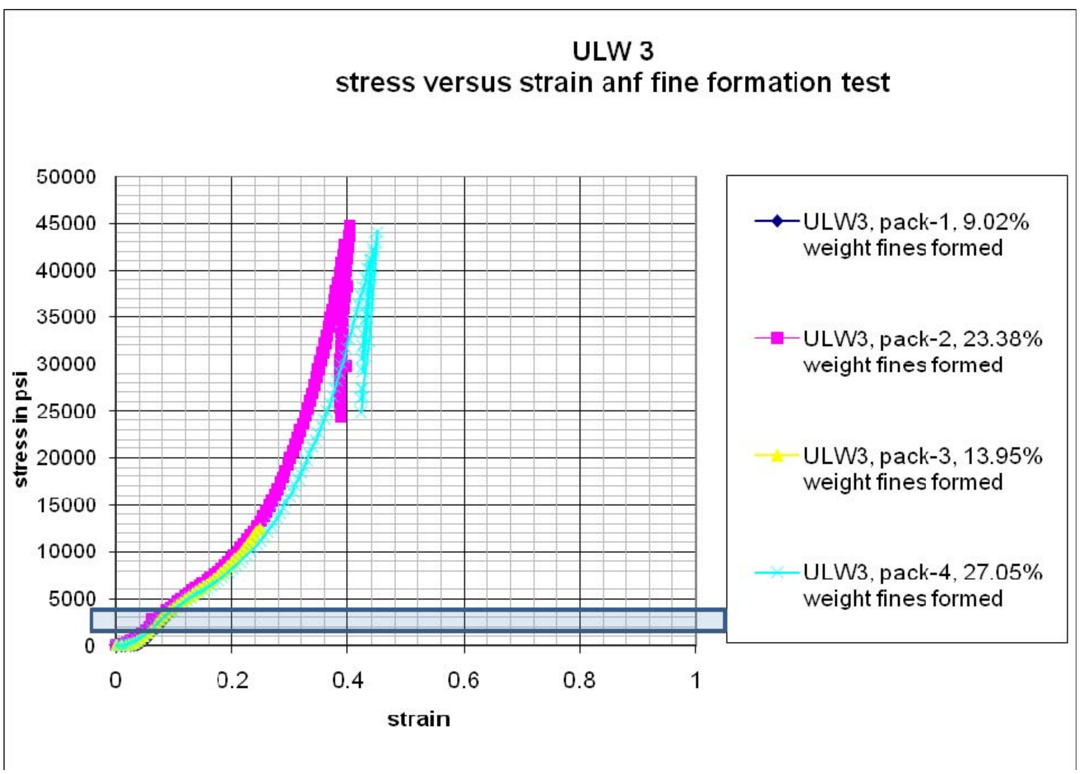

Fig. 11. Deformation of ULW-3 proppant pack at room temperature

The amount of proppant lost because of formation of finer particles for each of the tests is presented in Table 3. The fines generation in ULW1 and ULW2 are small.

	Maximum stress reached <= 45000 psi	**Maximum stress reached <= 45000 psi**	**Maximum stress reached <= 30000 psi**	**Maximum stress reached <= 30000 psi**
ULW 1	**4.76 %**	**6.06 %**	**1.49 %**	**4.48 %**
ULW 2	**1.41 %**	**2.59 %**	**1.33 %**	**1.36 %**
ULW 3	**23.38 %**	**27.05 %**	**9.02 %**	**13.95 %**

Table 3. Percent loss in weight of proppant pack due to formation of finer particles

Particle Stress Tests: After the strength test of the pack, we evaluated the strength behavior of individual proppant particles to examine the variation among the proppants. The mechanical behavior was tested at both room temperature and Barnett shale temperature (90^{o} C) to assess the change in behavior of proppants with the increase in temperature and also to determine the applicability of the proppants in Barnett shale.

ULW-1

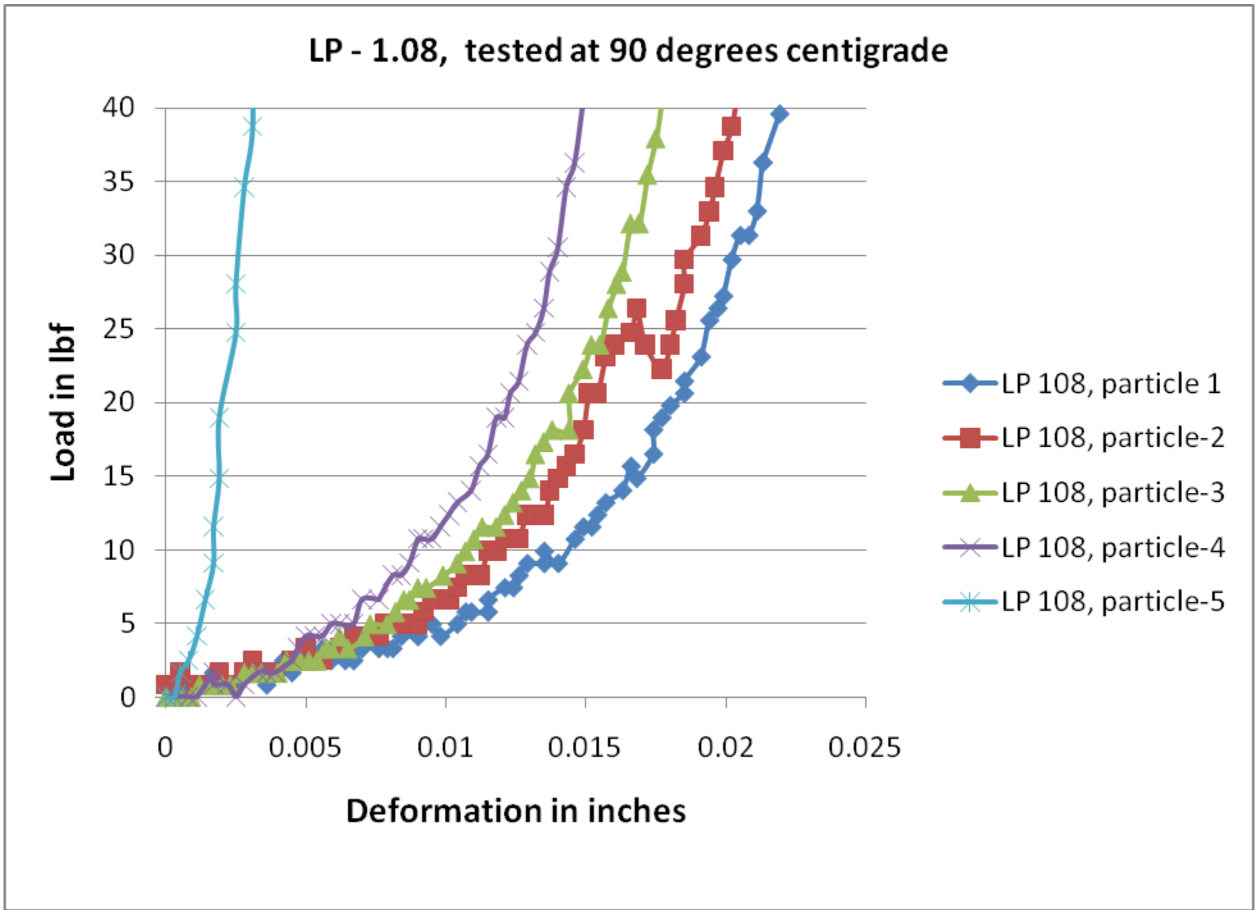

Fig. 12. Strength test of ULW-1 done at 90 °C

Fig. 12 shows the applied load and the resulting deformation for 5 single ULW-1 particles tested at 90 °C. Particles 1, 3-5 do not show definite failure points. Particle 2 fails at 27 lbf. Fig. 13 shows the applied load and the resulting deformation for 10 single particles tested at the room temperature. The load at failure is lower at the room temperature compared to that at 90 °C. These proppants can withstand the stress without getting crushed. This is due to the deformable nature of this polymeric proppant. Of course, these proppants deform under stress and reduce the fracture conductivity. Fracture conductivity would be studied in the next task when the applicability of the proppant can be determined.

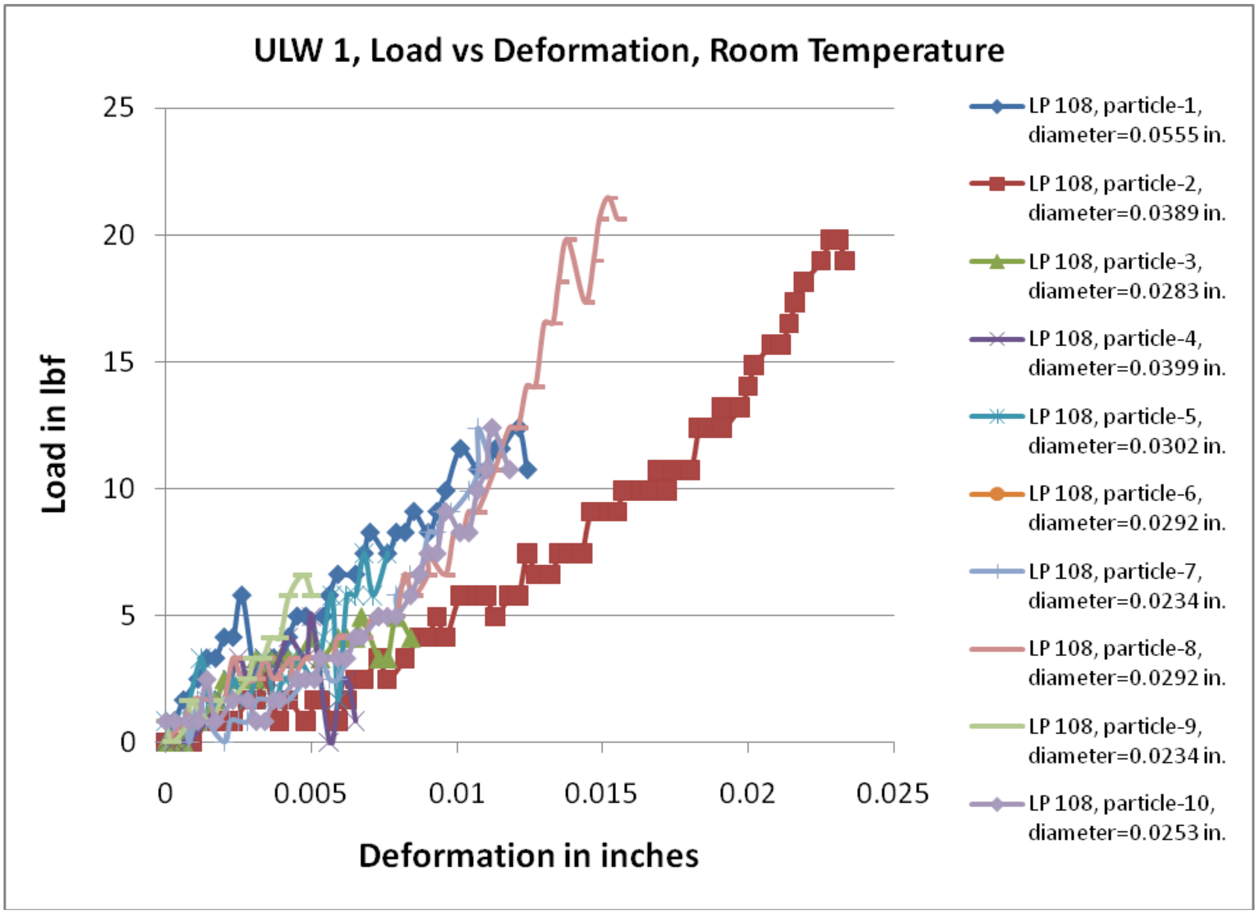

Fig. 13. Strength test of ULW-1 done at room temperature

ULW-2

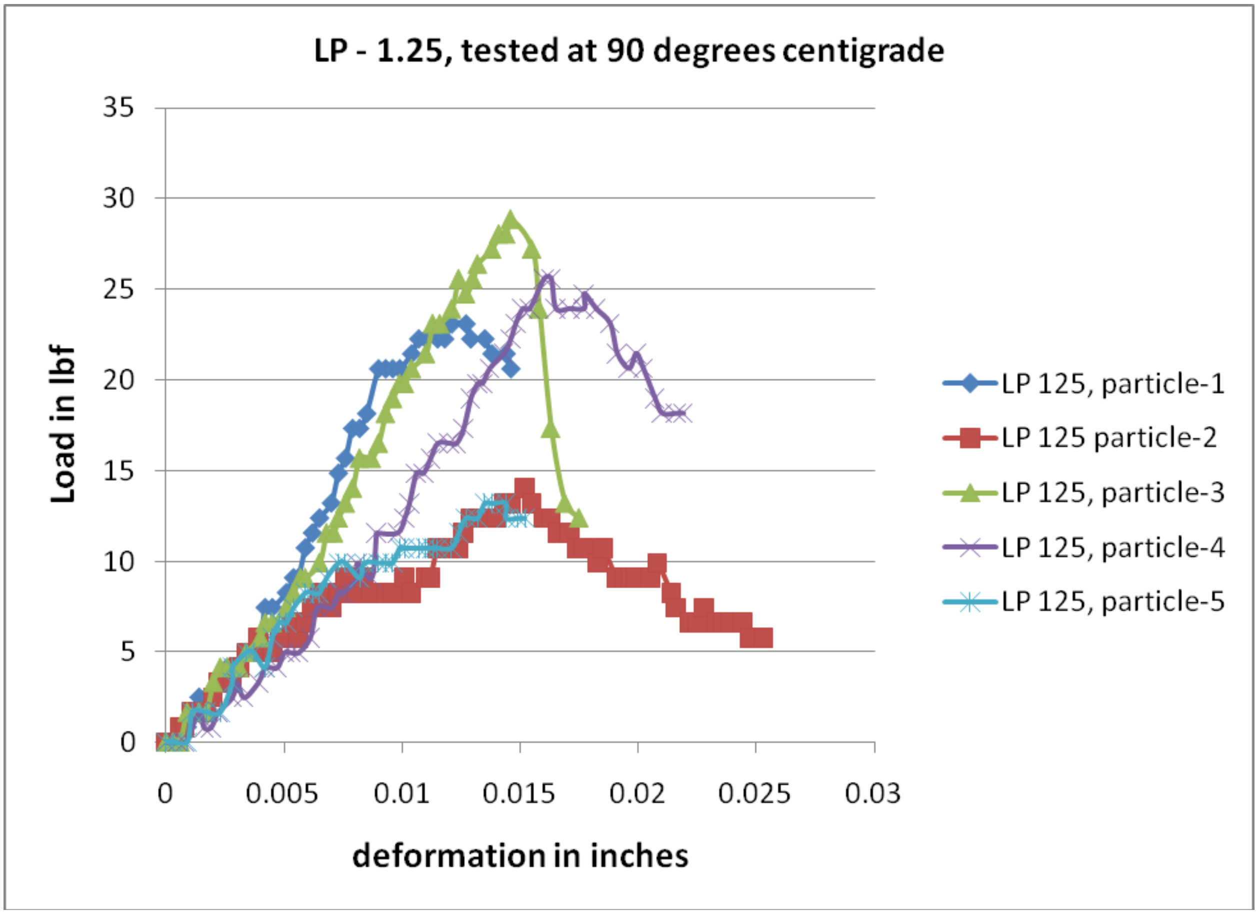

Fig. 14. Strength test of ULW-2 done at 90 ^{o}C

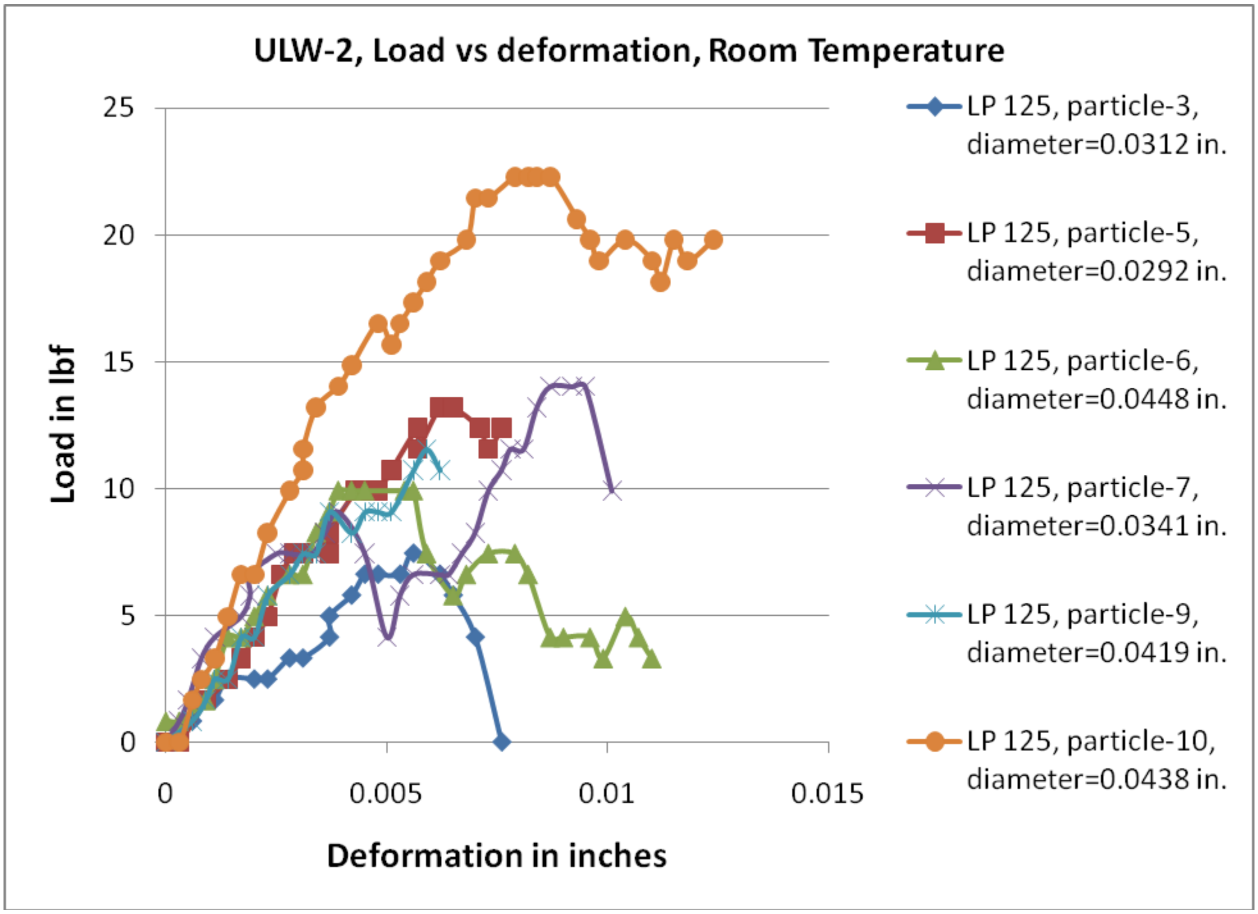

Fig. 15. Strength test of ULW-2 done at the room temperature

Figs. 14-15 show the applied load and the resulting deformation for 5 single ULW-2 particles tested at 90 ^{o}C and room temperature, respectively. At the higher temperature, the curves seemed to have stretched, i.e., deformations are larger for the same load applied, indicating increase in elasticity of the proppants with increasing temperature.

ULW-3

Figs. 16-17 show the applied stress and the resulting strain for 5 single ULW-3 particles tested at 90 ^{o}C and room temperature, respectively. The deformations at which individual particles fail are very low compared to those of the previous two proppants, indicating the brittle nature of ULW-3, a ceramic proppant.

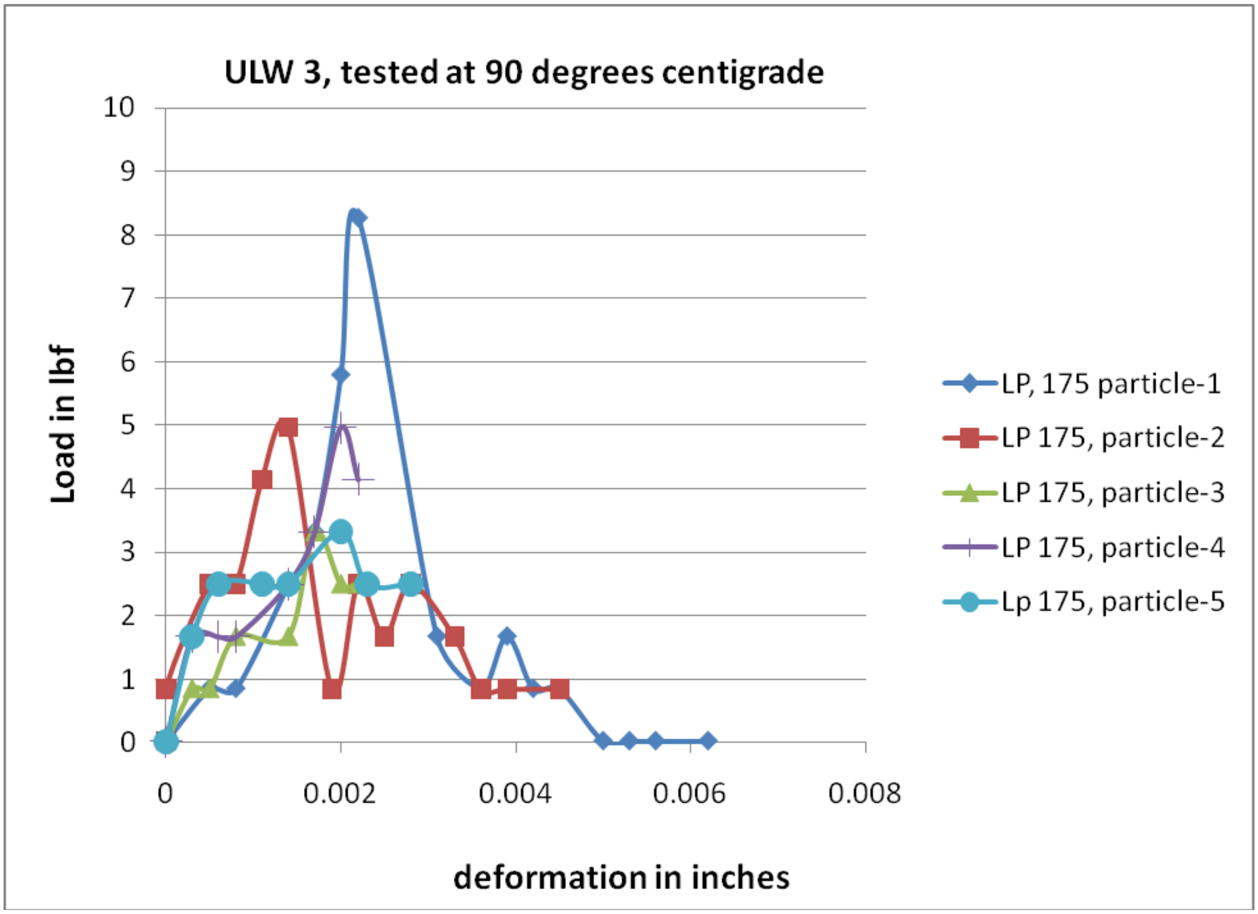

Fig. 16. Strength test of ULW-3 done at Barnett shale temperature of 90^{o} C

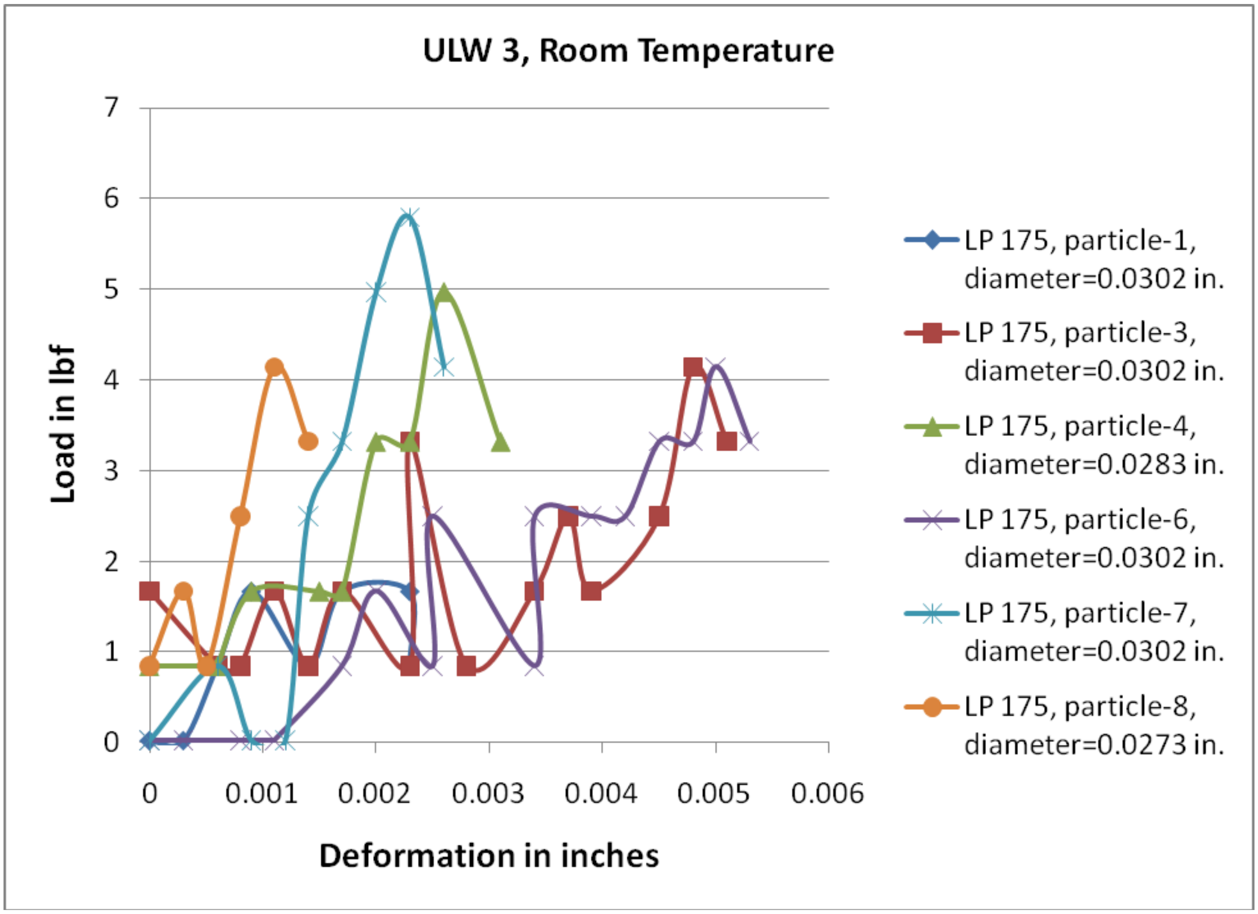

Fig. 17. Strength test of ULW-3 done at room temperature

Deformability: The load-deformation data for individual proppants have been converted to "effective stress" versus "effective strain" plots (Figs. 18-20). The values of stress and strain have been calculated on the basis of the initial dimensions of the particle. It is an effective value because the particles deform and the distribution of stress is not uniform on round particles. It is to be noted that the strain scale in all the three plots is kept constant to show the elasticity of proppants with respect to each other. A higher slope (or higher value of Young's modulus) indicates less elasticity.

Fig. 18 shows that ULW-1 is the most deformable. Many particles deform beyond an effective strain of 0.5 without failing. The Young's modulus varies significantly between particles. The largest particle had the highest Young's modulus in this sample. ULW-2 is not as deformable as ULW-1. Many of the particles fail at about 0.2 effective strain. Young's modulus for these particle are higher than those for ULW-1. ULW-3 particles are brittle; many particles fail below 0.2 effective strain. The Young's modulus is the highest for ULW-3 particles.

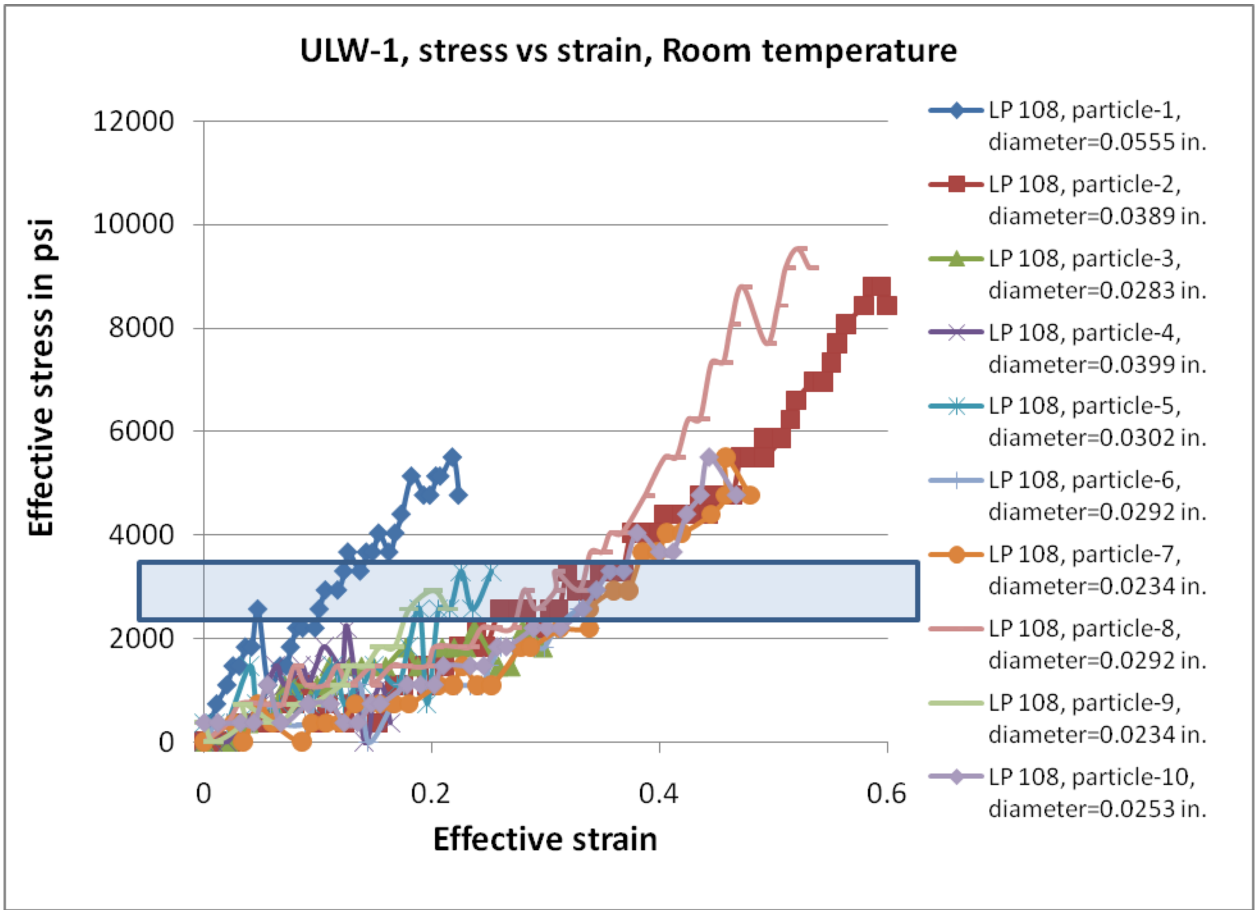

Fig. 18. Elastic modulus of ULW-1 at room temperature

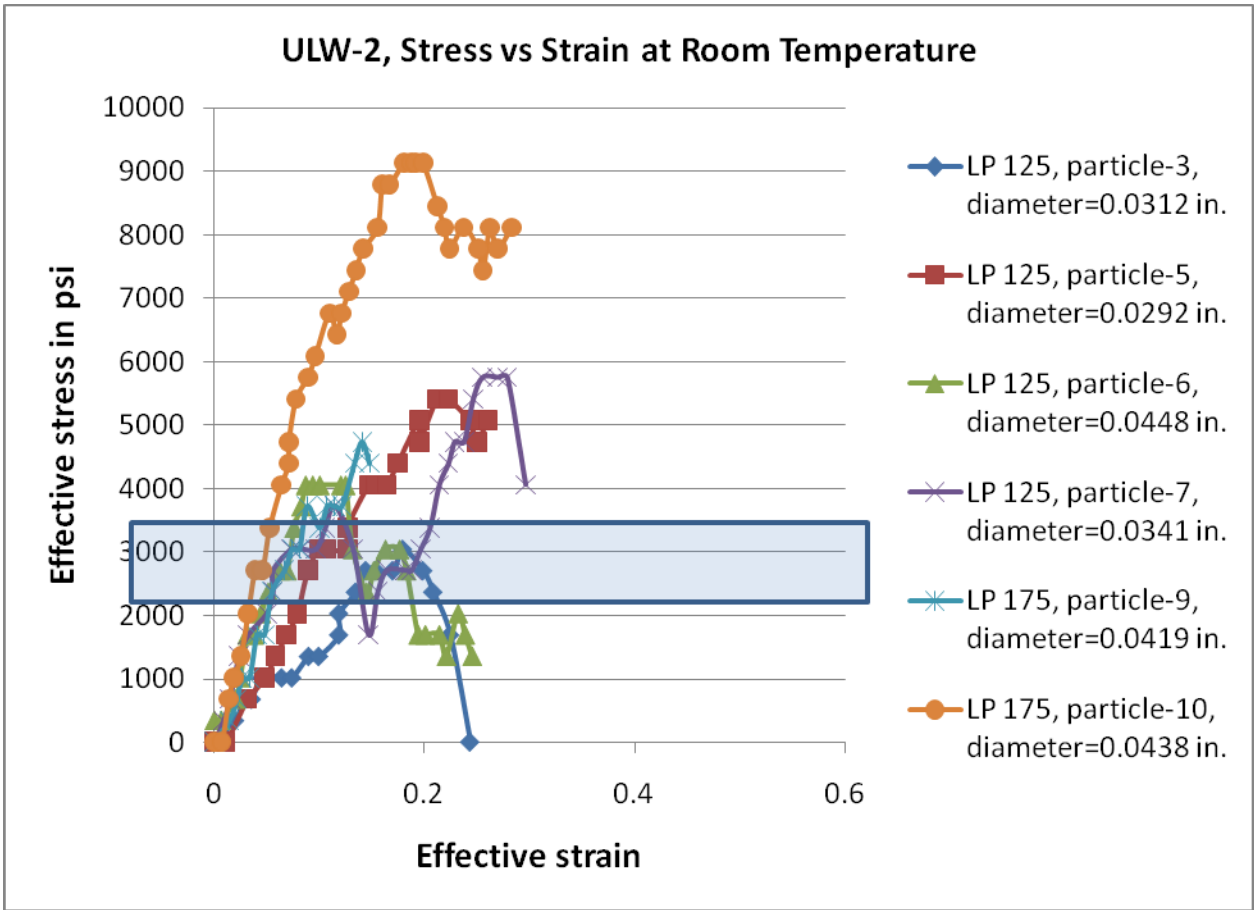

Fig. 19. Elastic modulus of ULW-2 at room temperature

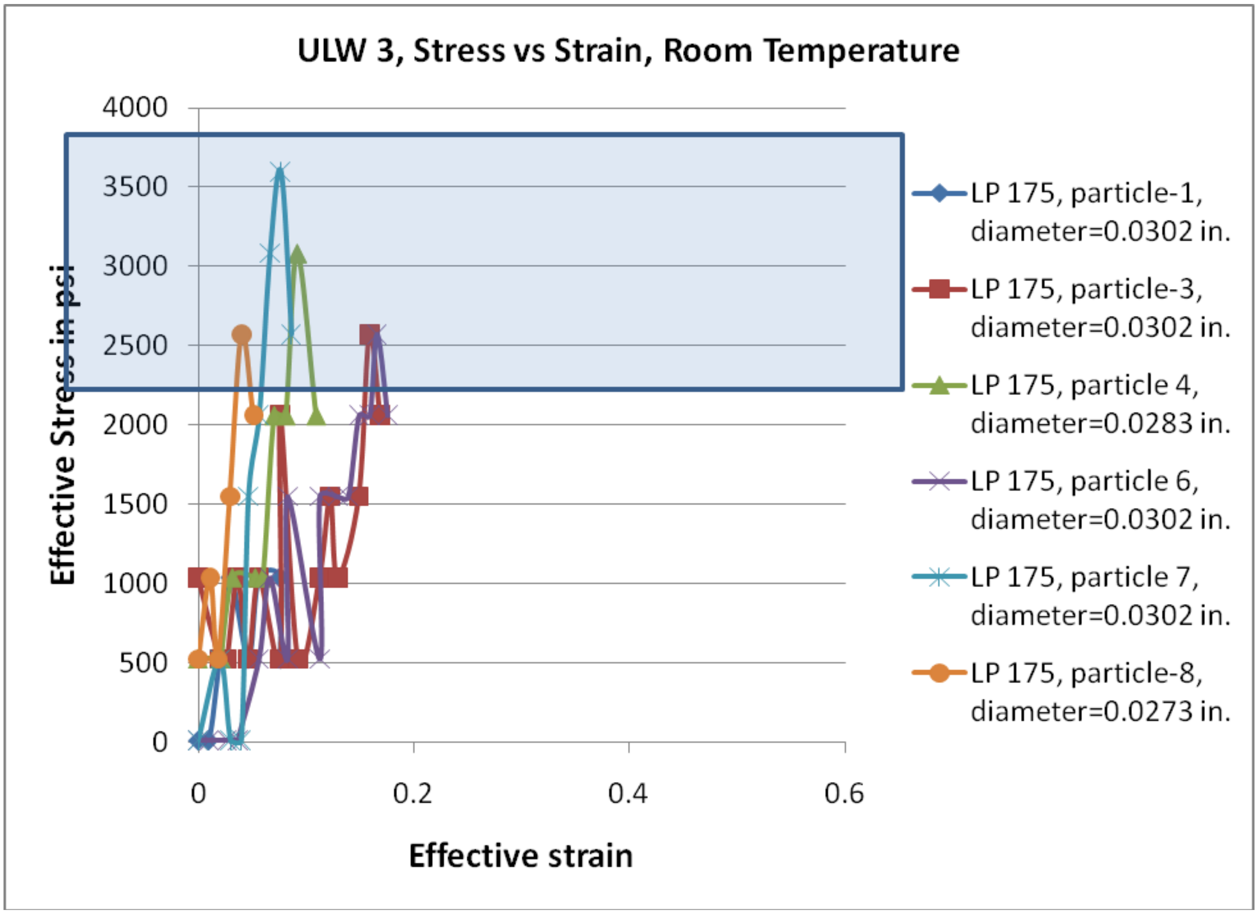

Fig. 20. Elastic modulus of ULW-3 at room temperature

Young's moduli are calculated from the above figures. At the room temperature, the Young's modulus of ULW-1 is around 15,400 psi. For ULW-2, at the same temperature, this value is higher around 38,900 psi. ULW-3 shows the highest value of Young's modulus of around 41,100 psi. At the end of each test, the particles were closely inspected with naked eye. It was found out, ULW-3 shattered into pieces confirming its brittle nature. ULW-1 particles stayed intact. They got flattened with increasing stress, but never got broken into several pieces. ULW-2 showed moderate deformability.

Conclusions

- ULW-1 is spherical, ULW-2 is slightly angular and UlW-3 is highly angular.
- Bulk density of ULW-1 is the least (0.6 gm/ml); that of ULW-3 is the highest (1.2 gm/ml). ULW-2 pack has an intermediate density (0.8 gm/ml).
- Of the three proppants tested, ULW-1 is the most deformable and ULW-3 is the most brittle. ULW-2 is fairly deformable. Measurement of fracture conductivity would determine whether the permeability loss due to deformation is small enough to make them useful in Barnett shale applications.
- ULW-1 and ULW-2 lose small amounts of proppants due to crushing of the proppant pack, whereas ULW-3 loses a significant amount due to formation of fines. After failure, ULW-3 leaves fine broken pieces, which can plug up the pores on the fracture surface.
- Of the three proppants tested, two of them, namely ULW-1 and ULW-2 were significantly strong to be able to endure the stresses expected in the Barnett shale conditions as individual particles. The failure points of ULW-3 particles tested lied marginally above the expected stresses in Barnett shale.
- All the proppant packs are significantly strong to endure the stresses expected in Barnett shale. Conductivity of these proppant packs must be measured before they can be recommended for high stress fractures.

Future Tasks

Task 5: Measuring the flow capacity of the proppant pack

Task 6: Foam fracturing fluid formulation

Acknowledgements

We thank RPSEA for the funding of the project and BJ services for providing us with the lightweight proppants. We appreciate the advice on this project from Drs. Q. Qu and T. J. Pisklak of BJ Services and Dr. A. Daneshy of Daneshy Consultants International.