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RESEARCH PAPER

New Insight on Deformation of Walnut/Ceramic Proppant Pack under Closure Stress in Hydraulic Fracture: Numerical Investigation

Mohammad Hasan Badizad[a], Amir Hossein Saeedi Dehaghani[b,*]

a. Department of Chemical and Petroleum Engineering, Sharif University of Technology, Tehran, Iran
b. Department of Petroleum Engineering, Faculty of Chemical Engineering, Tarbiat Modares University, Tehran, Iran

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Abstract

This study is an attempt to investigate the mechanical behavior of proppant packs deforming under compression loading. A generalized confined compression test (CCT) was simulated in the present study to investigate the deformation of walnut/ceramic proppants against compression. In this way, the CCT was simulated using ABAQUS explicit code. Unlike ordinary CCT, we obtained permeability of compressed packs through image processing of deformed packs. It was observed that a pack with small particles could markedly withstand deformation, however, at the expense of having lower permeability. Also, selecting a proper proppant pack strongly depends on the prevailing stress regime, where at low stress (<30 MPa) uniform walnut pack has the same permeability as a medley of walnut/ceramic pack. But, at greater stresses (> 40 Mpa), the pack with more ceramic is the best choice. Mixtures of walnut and ceramic proppants showed greatly strength improvement compared to similar cases with pure walnut granules. As a result, making use of such packing is highly recommended due to significant mechanical stability and also being of lower price compared to packs of pure ceramic granules.

Keywords:
Confined Compression Test,
Deformation,
Hydraulic fracture,
Permeability,
Proppant

Introduction

Hydraulic fracturing is a well-known process for enhancing the deliverability of oil/gas wells. This operation involves injecting high pressurized fluids into well bore in order to create massive conduits within an underground reservoir. Ultimately, frac pressure is released to retrieve production. During production, overburden stress tends to close fracture as if no treatment has ever taken! Therefore, small granules called *proppant* are typically injected along with fracturing fluid to pack fracture against closing stress [1,2].

Historically, proppants fall into three main categories, namely, natural sand, resin-coated sand, and ceramic. In this classification, natural sands are known as the lightest proppants well-suited for shallow reservoirs with closure stress at most 6000 psi. At higher stresses, these proppants are susceptible to severe crushing and generating free fines. Resin coated sands (RCS) are in essence pre-cured natural sands coated with phenolic materials. In this way, sands acquire higher roundness to withstand fragmentation at the grain-to-grain contacts. Ceramic is the strongest type of proppant, the most expensive as well, mainly composed of alumina (Al_2O_3)-silica clay which sometimes is regarded as sintered bauxite [3].

* Corresponding author
Email: asaeedi@modares.ac.ir (A. H. S. Dehaghani)

Although heavy ceramic particles are of the strongest resistance, economic considerations limit their applicability. Also, based on Stoke's law, they could undergo substantial settlement in fracturing fluid [4]. Accordingly, production engineers seek light, while strong enough, proppants to pack hydraulic fractures. Developing ultra-lightweight (ULW) proppants such as walnut shells is the focus of current industrial research which advantageously require carrying fluids of low viscosity [5].

For designing a propped hydraulic fracturing operation, one should realize the response of a propped fracture under varying stresses. To this end, some standard tests (metrics) are employed in industrial/academic laboratories to measure proppant pack deformation against applied compressive loading. For instance, in confined compression test (CCT) a proppant conglomerate is placed inside two horizontal moving platen and its deformation, that is, movement of plats, is recorded at varying applied stress while particles transversely restricted by sidewalls, as sketched in Fig. 1.

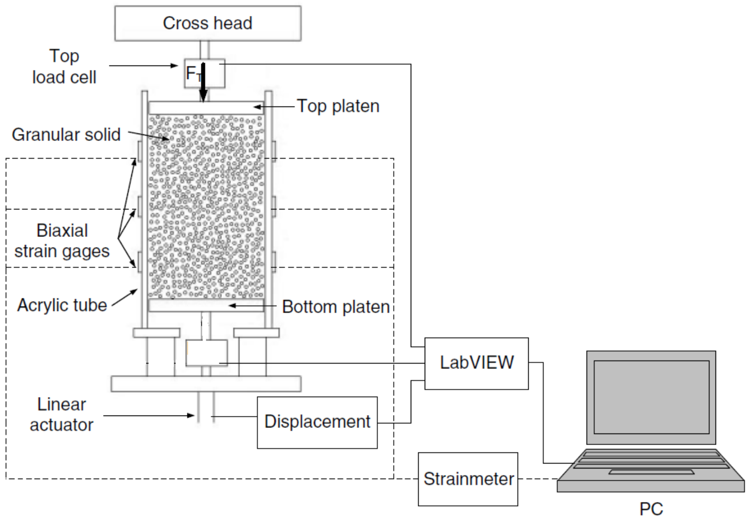

Fig. 1. Schematic of a conventional Confined Compression Test (CCT) [6].

Modeling a typical CCT requires taking mechanical behavior of individual constituting particles into account. To this end, the finite discrete element method (FDEM) was employed to model large deformation of granules under various stress regimes [7,8]. Despite great ability of FDEM to model realistic behavior of granular packs, its application demands massive computational power which makes it only suitable for two-dimensional (2D) simulations. For instance, Kulkarni et al. presumed plane strain condition to model the compression loading of proppant. In this manner, they took spherical particles as touching cylinders [9,10].

Before conducting an experiment like CCT, one should take a *screening* process through simulation to select the best proppant pack. Hence, the present study aims to take a step ahead through exploring deformation of walnut/ceramic pack under confined compression loading. For this purpose, ABAQUS 6.13 explicit code was employed to examine the evolution of porosity and permeability of walnut/ceramic pack under the compressive stress test. In following, first, the model structure will be elaborated and at the next section, a thorough sensitivity analysis will be performed on packs deformation behavior.

Model Description

Our modeling approach represents the real condition of a hydraulic fracture by extending the functionality of a routine CCT. A proppant pack was modeled as contacting circles enclosed by two plates, as illustrated in Fig. 2. This approach, in essence, presumes plane strain deformation in accordance with classical analytical models, e.g., PKN and KGD [11], to perform a computationally efficient simulation. As shown in Fig. 2, two rigid sidewalls, located 12 mm apart, prevent transverse movement of particles, only allowing net vertical deformation to proppant aggregate. Stress in the range of 20 to 60 MPa was uniformly distributed on the upper platen, depicted as arrows in Fig. 2. To represent realistic condition of underground reservoirs, lower and upper platens were taken to be shale with 6 mm apart and the upper one is allowed to move in the y-axis direction. As shown in Fig. 3, six different proppant packs were taken to evaluate their compression response, including: two uniform walnut packs with radius (0.5 or 1) mm (shortly UW-1 and UW-0.5), heterogeneous pack with grains of different sizes (shortly HW), two composite packs with different distribution of walnut and ceramic (shortly Comp-A and Comp-B) and uniform ceramic pack (shortly UC).

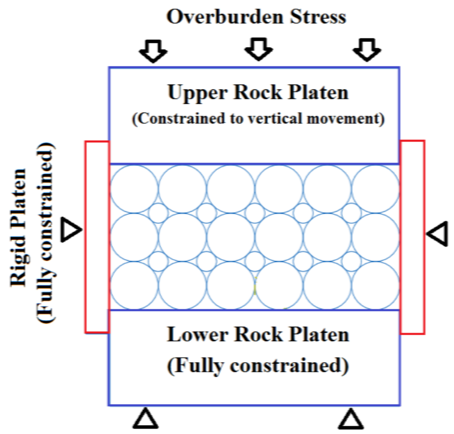

Fig. 2 Schematic of the confined compression test. Proppants are demonstrated as circles inside platens.

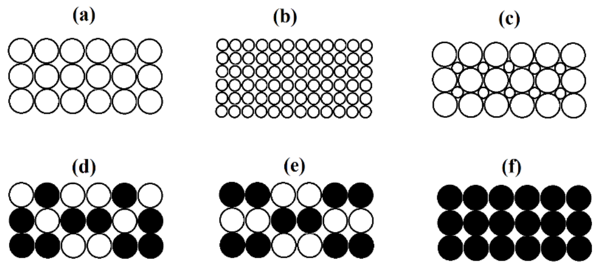

Fig. 3 Proppant pack configurations considered for simulation: (a) uniform walnut packs with radius 1 mm (UW-1); (b) uniform walnut packs with radius 0.5 mm (UW-0.5); (c) heterogeneous pack with grains of different sizes (HW); (d) composite pack (Comp-A); (e) composite pack (Comp-B); and (f) uniform ceramic pack (UC). Note open and filled circles denote walnut and ceramic, respectively.

In the mechanics of granules, contact interactions play an important rule, carrying stress between adjacent particles and wall/particle contacts. As such, the friction coefficient of 0.3 is typically used for calculating surface forces [9,12]. Also, to preserve problem symmetry while handling stress distribution at contact points, linear quadrilateral meshes of type CPS4R were employed to produce a grid structure of granules and platens, as shown in Fig. 4**.** Also, keyword NLGEOM was activated to enhance numerical stability during large displacement and excessive strain. To avoid numerical instability, model was built such that particles closely touched each other and surfaces of confining platens. The number of constituting components, elements, and nodes, are presented in Table 1.

Proppants under consideration are walnut shell and ceramic. Walnut is an elastic-perfectly plastic substance with Young's modulus 3.7 GPa and specific gravity 1.25 [13]. To represent the macroscopic effect of micro-fractures on inelasticity of ceramic, isotropic concrete damage plasticity was employed to account for ceramic deformation. For detailed description consult [14]. Mechanical properties of materials are presented in Table 2.

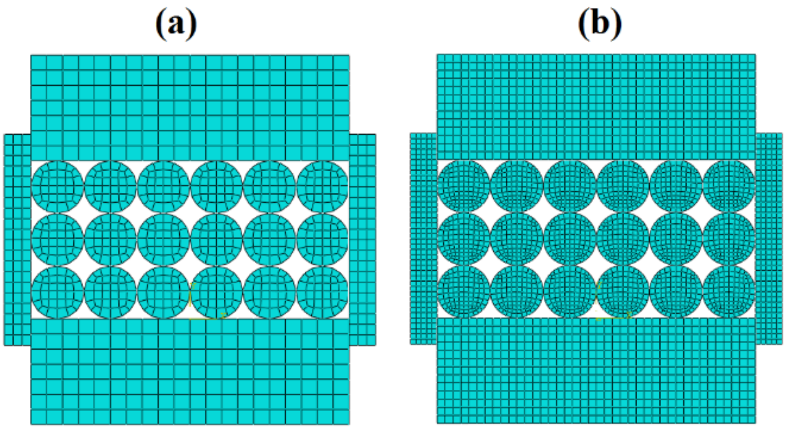

Fig. 4. Mesh structures applied for constructing the finite-element model: (a) coarse grid structure used in all simulation; and (b) finer mesh structure used for sensitivity analysis of the model.

Table 1. Number of nodes and elements in the grid structure of different model components.

Object	Number of nodes	Number of elements
Great circle	41	32
Fine circle	22	16
Horizontal Platen	168	140
Vertical Platen	84	60

Table 2. Material specification of proppants and confining platens (9).

Material	Specific gravity	Young's modulus (GPa)	Poisson ratio
Walnut	1.25	3.7	0.3
Ceramic	2.6	259	0.25
Shale	2.5	12	0.22

Results and discussion

At this section, we analyze the effect of pack specifications on its mechanical response. Fig. 5a illustrates stress applied on the top moving platen of CCT against non-dimensional platen displacement, i.e., the net displacement divided by initial pack thickness. Noteworthy, the mechanical response of granular systems is much more complex than simple solid rock-like samples, normally employed to obtain stress-strain curves. Therefore, though stress-strain curves are typically smooth, one could notice a fairly erratic response of proppants under deformation, shown in Fig. 5a. This observation is attributed to contact interactions dominated at touching particles and also the progressive deflection of granules during compression. In this sense, UW-0.5, which contains more particles (Fig. 3b), demonstrates the strongest erratic response, as noticed in Fig. 5a.

To evaluate the sensitivity of our model on gridding (Fig. 4a), a case with finer meshes was constructed (Fig. 4b). Interestingly, both models are of identical compaction response. Hence, for convenience, the rest of the simulations were carried out based on the coarser mesh.

As seen in Fig. 5a, all packs initially follow a similar trend up to ~30 MPa, supposedly due to slight rearrangement and slippage of contacting spheres. Noteworthy, composite packs (Comp-A and B) and fine grain pack (HW) demonstrate a more distinct erratic compression response which highlights the substantial influence of particles mechanical interactions. On the other hand, at high applied stresses (greater than 45 MPa as shown in Fig. 5a) all displacement curves level off, demonstrating a stabilized response. It could be argued that particles are markedly vulnerable to deformation in case of low stress. However, after passing a transient stress interval (here in 30 to 40 MPa) which characterizes steadily crushing of proppants, they would deform so intense that compressed pack takes the form of a solid rectangle. Simply put, particles mechanical interactions are immaterial at severe compaction. This argument is supported by a notable, linear trend of HW pack. Also, since ceramic pack (UC) is much more rigid compared to walnut, its particles undergo less crushing, thus having a nearly linear displacement curve. UC requires threshold stress to show marked compression.

According to Fig. 5a, increasing number of ceramic proppants renders a pack higher strength, that is, packs displacement follows order: UC<Comp-B<Comp-A. Also, the arrangement of ceramic and walnut particles slightly influences on pack's strength response, as evident by the slight departure of Comp-A and Comp-B.

Areal porosity of deformed configurations (Fig. 5b) was obtained at varying stresses using image processing toolbox of MATLAB. Notably, there is a direct relation between porosity variation (Fig. 5b), and platen displacement (Fig. 5a). Clearly, in absence of applied stress, HW is of at minimum initial porosity (~0.15) compared to other packs with porosity ~ 0.22. Despite low initial porosity of HW, other packs, except for UC, are much more susceptible to compression, especially at high loading (greater than 40 MPa). Noticeably, all particles configurations, except for UC, take identical deformed structure at severe compression, marked by the red circle in Fig. 5b. This observation points to an important practical matter that uniform-sized proppant packs does not necessarily result in an efficient frac and pack operation. That is to say, proppants inhomogeneity provides stronger packing against the closing force of fracture faces during the lifespan of a hydraulic fracture.

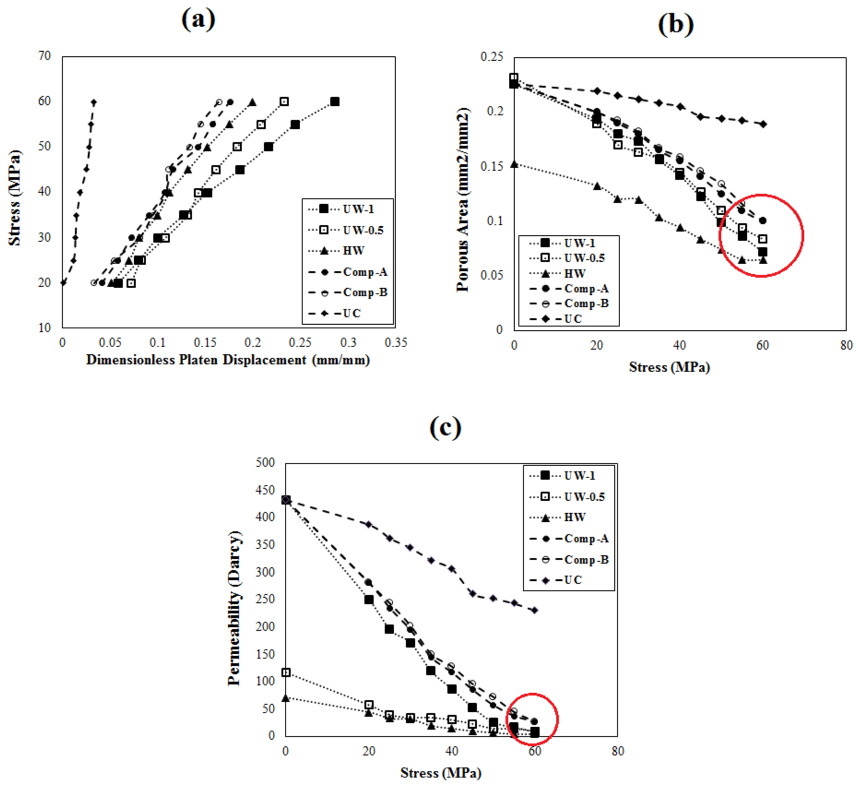

Fig. 5. Mechanical response of different packs at varying stress: (a) dimensionless displacement; (b) porosity; and (c) permeability. Red circles mark the approach of porosity and permeability of different packs to each other at intense stress regime.

Fracture permeability reflects proppant digenesis properties. Conventionally, well-known Kozeny-Carman expression is used to estimate pack permeability (k), given by [15]:

$$k(darcy) = 3.631 \times 10^6 \frac{d^2 \phi^3}{(1-\phi)^2} \tag{1}$$

Where d represents grains average diameter in inch. and ϕ denotes porosity. By using the above expression and porosity values acquired through image processing, one could calculate the permeability of deformed packs, shown in Fig. 5c. HW configuration with fine and coarse granules demonstrated the lowest permeability of all compression loads. This is due to the contribution of finer particles. Regarding Eq. 1, permeability of a granular system is proportional to squared of constituting particles diameter. As a matter of fact, as seen in Fig. 5c, UW-0.5 closely follows the permeability trend of HW, both have much lower permeability than a uniform pack with particles radius 1 mm (UW-1). As a result, small constituting proppants, though of identical stiffness to coarser ones, could result in significantly low permeability which reduces the conductivity of a propped fracture. On the other hand, although using heterogeneous and composite packs seems intuitively of greater strength, as also verified in Fig. 5a, however, the presence of finer granules could spoil pack hydraulic capacity, i.e., leading to lower permeability.

As expected, ceramic pack (UC) is of highest permeability corresponding to its highest porosity. But, as mentioned earlier, using purely ceramic proppants could severely violate the economic limit of a successful packing operation. Overall, based on the permeability variation shown in Fig. 5c, at weak to moderate stresses (up to 30 MPa), heterogeneous pack of walnut works as efficient as composite ones (comprised of both walnut and ceramic), all suitable for packing purpose. But, at severe stress regimes (herein upper than 40 MPa), only uniform ceramic pack could effectively maintain fracture permeability. Therefore, hydraulic fracturing at deep wells requires a pack mainly composed of ceramic proppants.

Conclusions

This study was an attempt to investigate the mechanical behavior of proppant packs deforming under compression loading. In this way, confined compression test was simulated using ABAQUS 6.13 explicit code with taking walnut and ceramic proppants as 2D circles. To summarize, the following main conclusions were drawn:

1. For uniform walnut packs, size of proppants was of significant effect, where, adding finer ceramic particles to such configurations could greatly improve pack strength against compression at the expense of obtaining lower permeability.
2. To design a frac and pack operation, one should focus on the variation of fracture permeability at varying level of formation stress. In other words, pack stiffness is not alone a screening factor, and resultant permeability reflects the suitability of a proppant pack. In this respect, the heterogeneous pack (containing fine particles among bigger ones) observed to be of low permeability, even though showing great compressive strength.
3. Mixtures of walnut and ceramic proppants showed greatly strength improvement compared to similar cases with pure walnut granules. As a result, making use of such packing is highly recommended due to significant mechanical stability and also being of lower price compared to packs of pure ceramic granules.

References

[1] Liang F, Sayed M, Al-Muntasheri GA, Chang FF, Li L. A comprehensive review on proppant technologies. Petroleum. 2016 Mar 1;2(1):26-39.
[2] Yao Y, Wang W, Keer LM. An energy based analytical method to predict the influence of natural fractures on hydraulic fracture propagation. Engineering Fracture Mechanics. 2018 Feb 15;189:232-45.

[3] Patel PS, Robart CJ, Ruegamer M, Yang A. Analysis of US hydraulic fracturing fluid system and proppant trends. InSPE Hydraulic Fracturing Technology Conference 2014 Feb 4. Society of Petroleum Engineers
[4] Tomac I, Gutierrez M. Micromechanics of proppant agglomeration during settling in hydraulic fractures. Journal of Petroleum Exploration and Production Technology. 2015 Dec 1;5(4):417-34.
[5] El-M. Shokir EM, Al-Quraishi AA. Experimental and numerical investigation of proppant placement in hydraulic fractures. Petroleum Science and Technology. 2009 Oct 21;27(15):1690-703.
[6] Peng HH, Lin CK, Chung YC. Effects of Particle Stiffness on Mechanical Response of Granular Solid Under Confined Compression. Procedia Engineering. 2014 Jan 1;79:143-52.
[7] Munjiza A, Owen DR, Bicanic N. A combined finite-discrete element method in transient dynamics of fracturing solids. Engineering computations. 1995 Feb 1;12(2):145-74.
[8] Guo J, Luo B, Lu C, Lai J, Ren J. Numerical investigation of hydraulic fracture propagation in a layered reservoir using the cohesive zone method. Engineering Fracture Mechanics. 2017 Dec 1;186:195-207.
[9] Kulkarni MC, Ochoa OO. Creating novel granular mixtures as proppants: Insights to shape, size, and material considerations. Mechanics of Advanced Materials and Structures. 2017 May 19;24(7):605-14.
[10] Xia L, Yvonnet J, Ghabezloo S. Phase field modeling of hydraulic fracturing with interfacial damage in highly heterogeneous fluid-saturated porous media. Engineering Fracture Mechanics. 2017 Dec 1;186:158-80.
[11] Carrier B, Granet S. Numerical modeling of hydraulic fracture problem in permeable medium using cohesive zone model. Engineering Fracture Mechanics. 2012 Jan 1;79:312-28.
[12] Kulkarni MC, Ochoa OO. Mechanics of light weight proppants: A discrete approach. Composites Science and Technology. 2012 May 2;72(8):879-85.
[13] Kulkarni MC, Ochoa OO. Light weight composite proppants: Computational and experimental study. Mechanics of Advanced Materials and Structures. 2012 Jan 1;19(1-3):109-18.
[14] ankowiak T, Lodygowski T. Identification of parameters of concrete damage plasticity constitutive model. Foundations of Civil and Environmental Engineering. 2005 Jun;6(1):53-69.
[15] Xu P, Yu B. Developing a new form of permeability and Kozeny–Carman constant for homogeneous porous media by means of fractal geometry. Advances in Water Resources. 2008 Jan 1;31(1):74-81.