

Repedés konduktivitást befolyásoló tényezők, köztük a „proppant pack” és a kőzetmechanikai jellemzők vizsgálata

Investigation of parameters influencing fracture conductivity including proppant pack properties and rock mechanical characteristics

Lengyel Tamás

ME Alkalmazott Földtudományi Kutatóintézet

2017.01.10 -11.

www.afki.hu

SZÉCHENYI 2020



MAGYARORSZÁG
KORMÁNYA

Európai Unió
Európai Regionális
Fejlesztési Alap



BEFEKTETÉS A JÖVŐBE

Agenda

- Intuition – Purpose of Research
- Derivation of the Model
- Sensitivity Test Results
- Proppant Selection Method
- Field Example
- Conclusion



„Új kutatási irányok a földi energiaforrások hasznosításához
kapcsolódóan” című szakmai tudományos konferencia

Purpose of Research & Intuition

- Aim of HF is productivity improvement
- PI is highly dependent on F_c
- Interaction between proppant and fracture surface
- Investigation of proppant embedment



Fig. 1: Proppants in fracture

2017.01.10 -11.

www.afki.hu

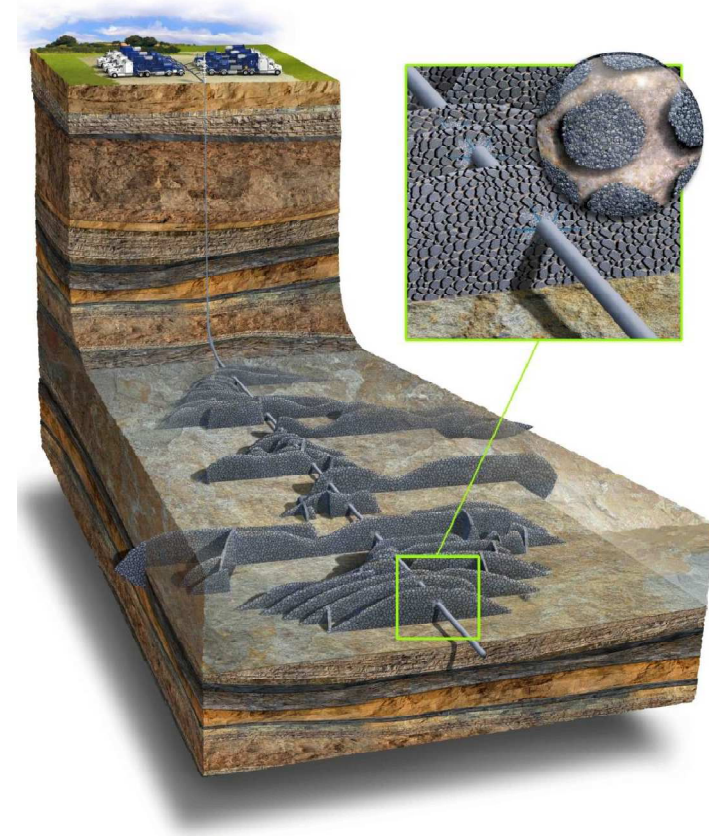


Fig. 2: Illustration of propped fractures

The analytical model

(Li et al.)

- Only mathematical and physical considerations
- Can be used in wide range
- Assumptions must be taken into account
- Boundary conditions

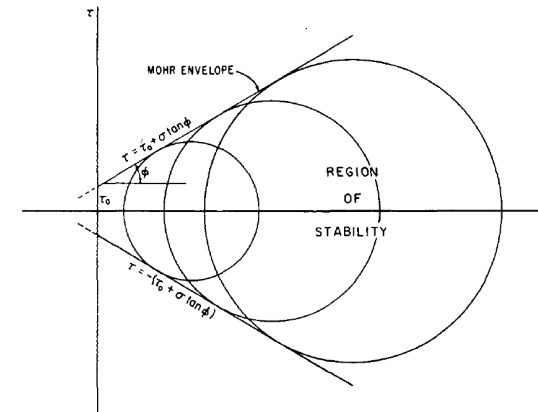


Fig. 3: Boundary condition with Mohr circles

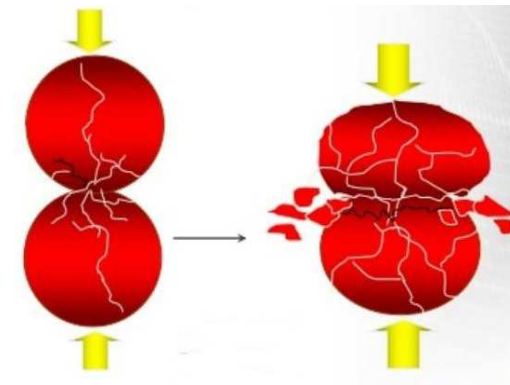


Fig. 4: Illustration of proppant crush

Derivation of the model

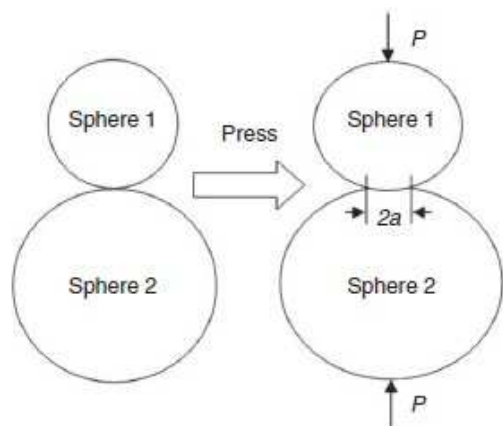


Fig. 5: Two mutually squeezed elastic spheres

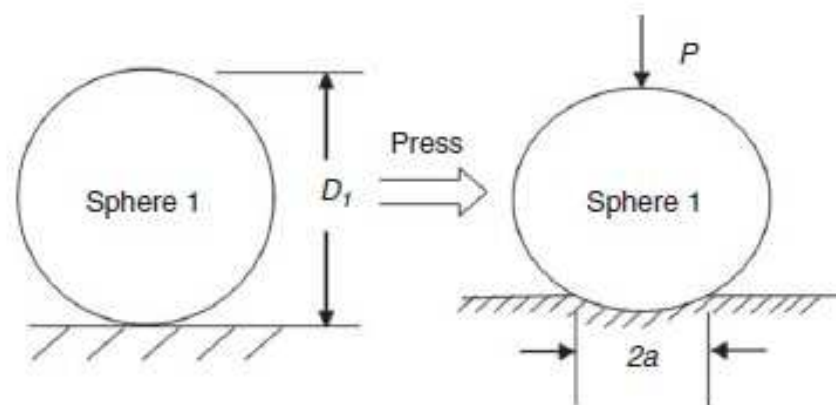


Fig. 6: Mutually squeezed plate and sphere

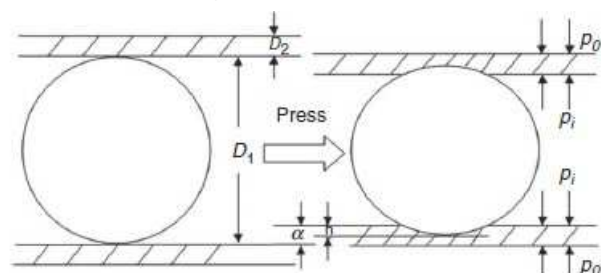
$$\alpha = 1.04D_1(K^2pC_E)^{\frac{2}{3}} + D_2\frac{p}{E_2}$$

$$\beta = 1.04D_1\left(K^2p\frac{1-\nu_1^2}{E_1}\right)^{\frac{2}{3}}$$

$$h = 1.04D_1(K^2p)^{\frac{2}{3}}\left[\left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right)^{\frac{2}{3}} - \left(\frac{1-\nu_1^2}{E_1}\right)^{\frac{2}{3}}\right] + D_2\frac{p}{E_2}$$

Real Situation

Monolayer



$$\alpha = 1.04D(K^2p)^{\frac{2}{3}} \left\{ \left(\frac{1-\nu_1^2}{E_1} \right)^{\frac{2}{3}} + \frac{D_1}{D} \left[\left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right)^{\frac{2}{3}} - \left(\frac{1-\nu_1^2}{E_1} \right)^{\frac{2}{3}} \right] \right\} + D_2 \frac{p}{E_2}$$

$$\beta = 1.04D \left(K^2p \frac{1-\nu_1^2}{E_1} \right)^{\frac{2}{3}}$$

$$h = 1.04D_1(K^2p)^{\frac{2}{3}} \left[\left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right)^{\frac{2}{3}} - \left(\frac{1-\nu_1^2}{E_1} \right)^{\frac{2}{3}} \right] + D_2 \frac{p}{E_2}$$

Fig. 7: Stress analysis for a single proppant

Multilayer

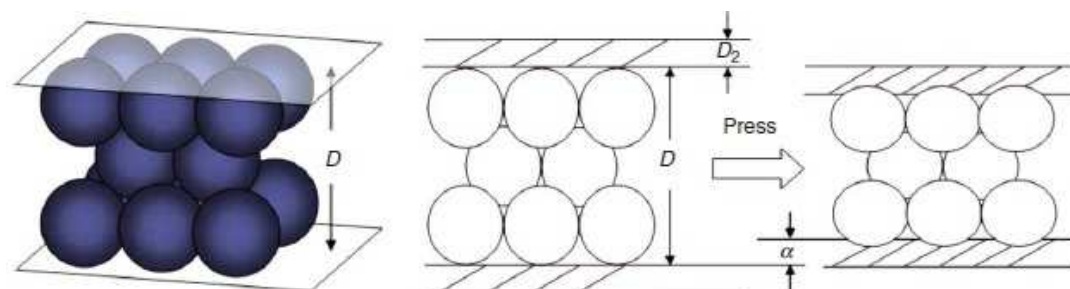


Fig. 8: Proppant paving in multiple layers

Deformation:
superposition of each
layer's deformation

Embedment is the same

Fracture Conductivity

Affected by:

- Proppant size
- Closure pressure
- Elastic modulus and Poisson's ratio of proppant
- Elastic modulus and Poisson ratio of the formation
- Initial fracture aperture

$$\phi_0 = \frac{4\sqrt{2}R_1^3 - \frac{4}{3}\pi R_1^3}{4\sqrt{2}R_1^3} = 0,25951$$

$$\phi = \frac{D\phi_0 - 2\beta}{D - 2\beta}$$

$$r_0 = 1000 \frac{2\sqrt{3} - 3}{3} R_1$$

$$r = \left(\frac{D - 2\beta}{D} \right) r_0$$

$$\tau_0 = \frac{\sqrt{\left(\frac{2}{3}R_1\right)^2 + \left(\frac{\sqrt{2}}{3}R_1\right)^2}}{\frac{2}{3}R_1} = \frac{\sqrt{6}}{2}$$

$$\tau = \sqrt{\left(\frac{D - 2\beta}{D} \right)^2 (\tau_0^2 - 1) + 1}$$

$$k = \frac{\Phi r^2}{8\tau^2}$$

$$F_{CD} = kw = \frac{(D\phi_0 - 2\beta)(D - 2\beta)r_0^2}{80 \left[\left(\frac{D - 2\beta}{D} \right)^2 (\tau_0^2 - 1) + 1 \right] D^2} (D - 2\alpha)$$

Sensitivity Test: Effect of proppant size

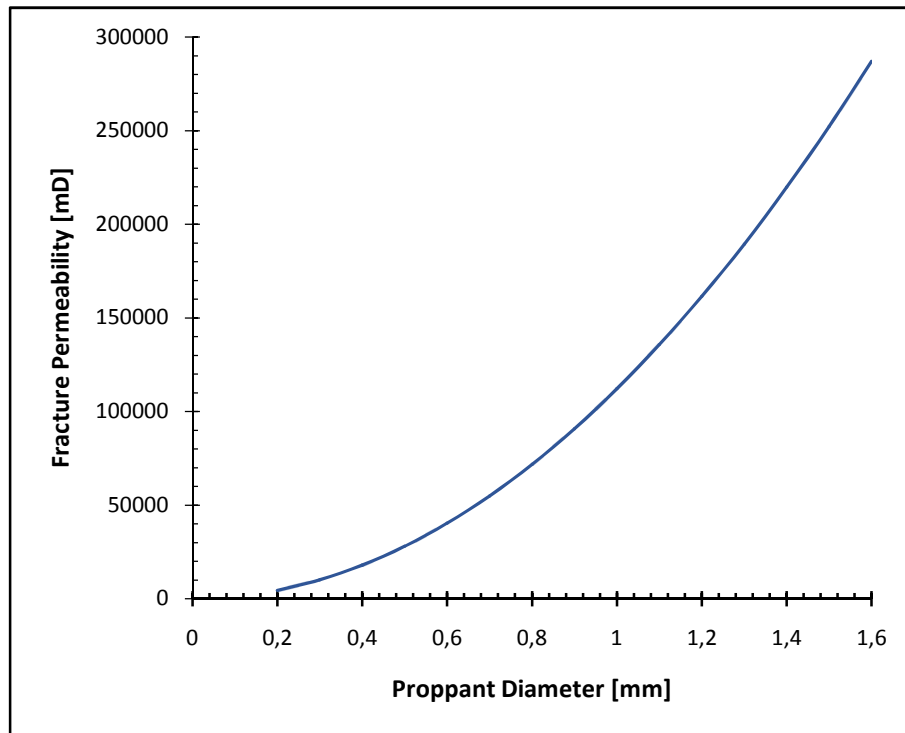


Fig. 9: Fracture permeability in function of proppant diameter

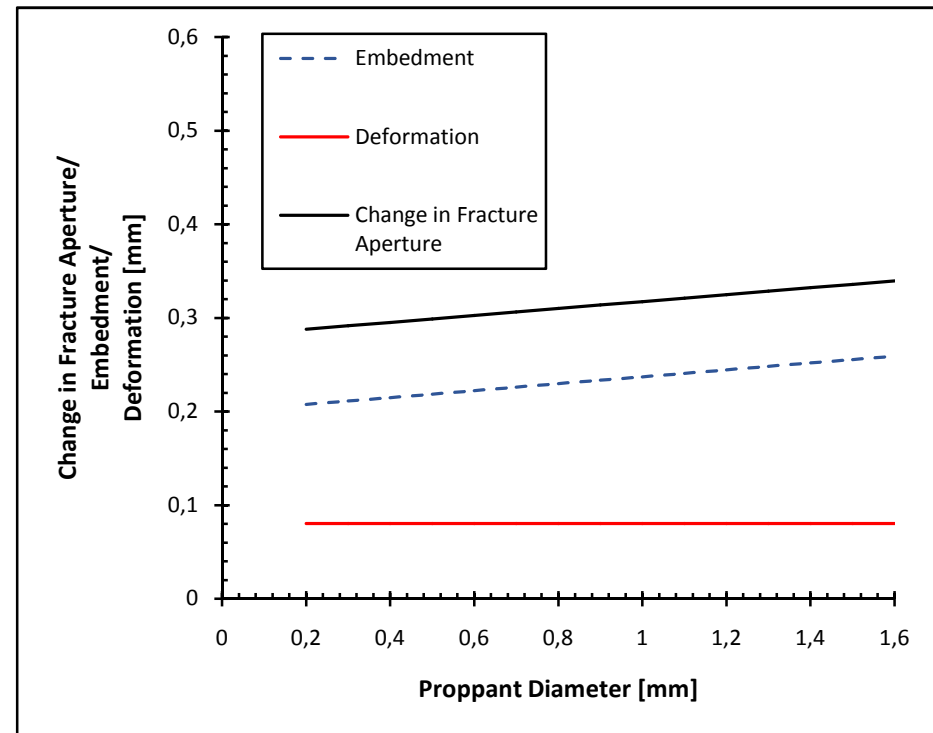


Fig. 10: Relationship between the three variables and proppant diameter

Sensitivity Test: Effect of proppant size

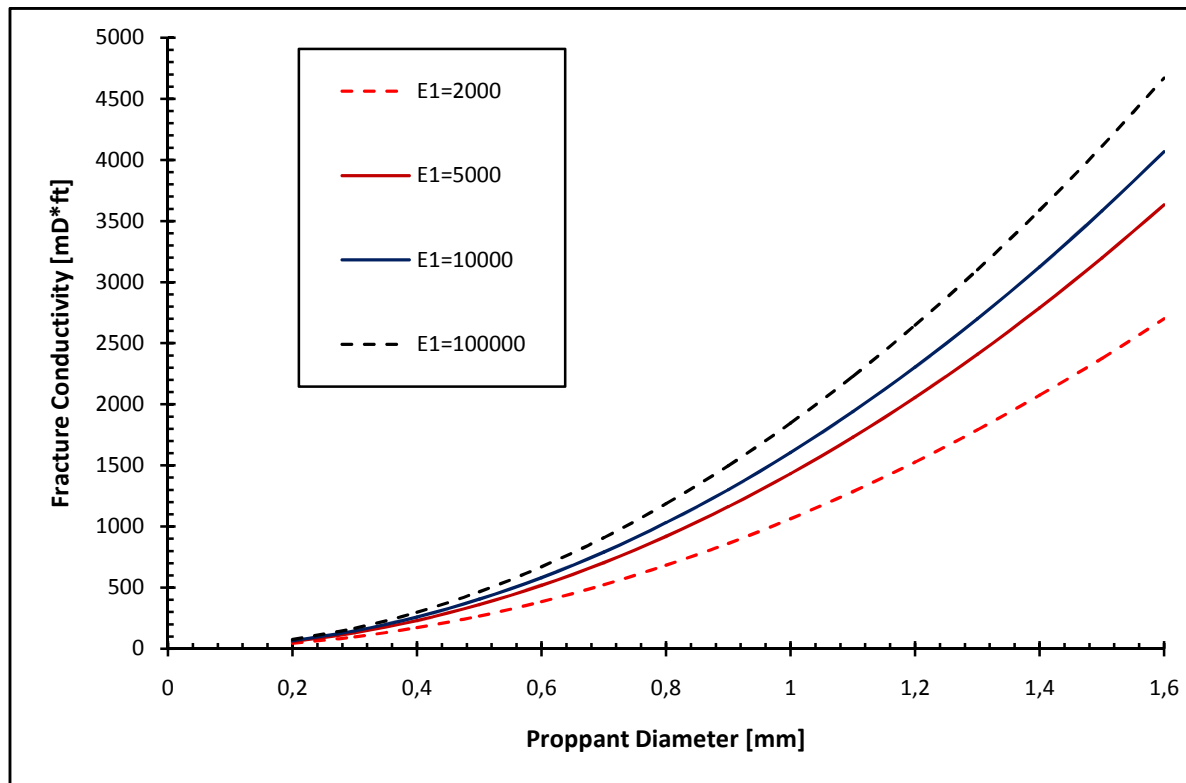


Fig. 11: Fracture conductivity as a function of proppant diameter and elastic modulus of proppant

Sensitivity Test: Effect of closure pressure

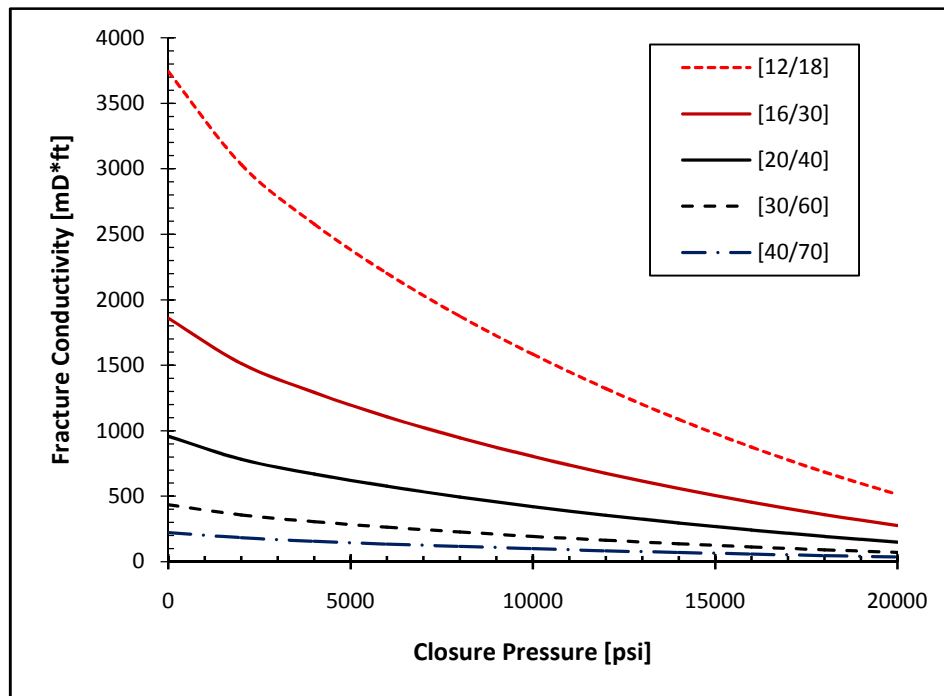


Fig. 12: Fracture conductivity as a function of closure pressure and proppant size

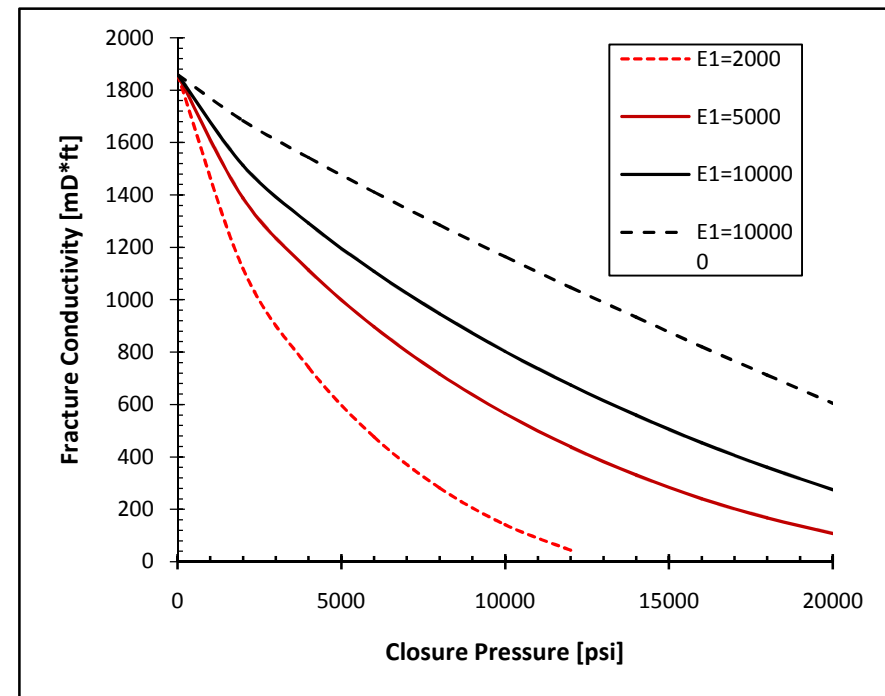


Fig. 13: Fracture conductivity as a function of closure pressure and elastic modulus of proppant

Proppant Selection

Combination of the analytical analysis system
and the Unified Fracture Design (UFD) model

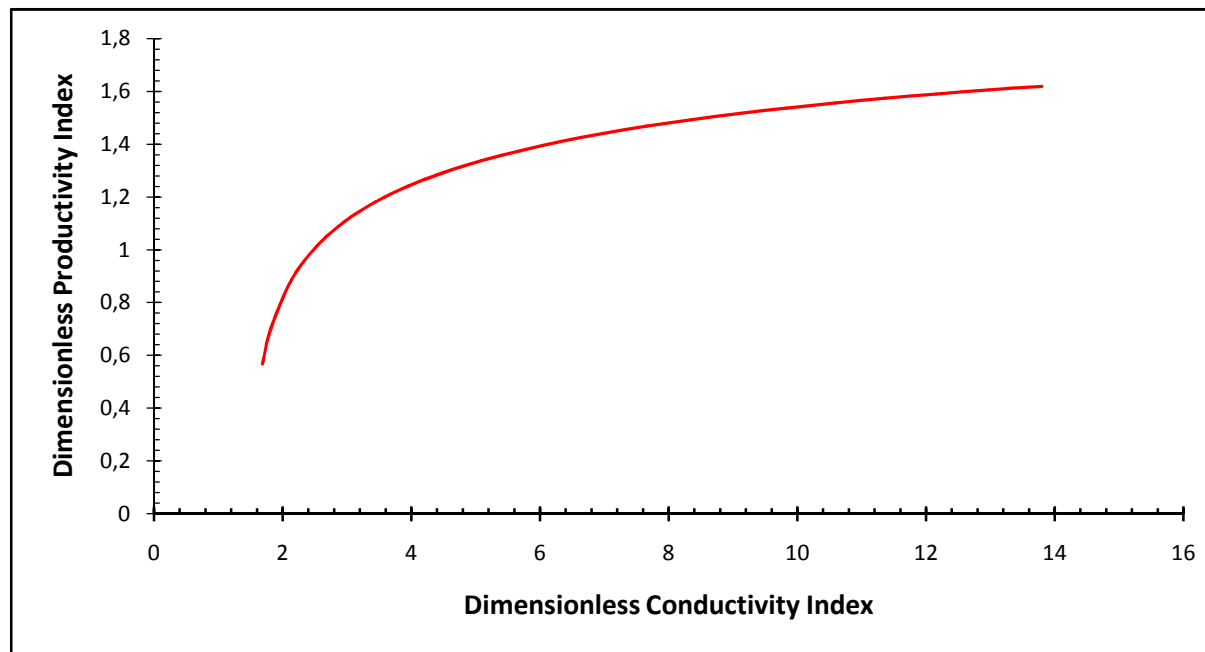


Fig. 14: Dimensionless productivity index as a function of dimensionless conductivity index

$$\Phi = 1 - \frac{C_p}{w\rho_p}$$

$$w = \frac{C_p}{(1 - \phi)\rho_p}$$

$$C_{fD} = \frac{k_f w}{k X_f}$$

Field Example

Proppant Data

Proppant Permeability is calculated based on the following parameters:

BH Static Temperature: 123 degC
 Stress on Proppant: 307 bars
 Propped Fracture Conc.: 4.88 kg/m2
 Average Young's Modulus: 7.277E+06 psi

Proppant Data				
Proppant Name	Specific Gravity	Mean Diameter (mm)	Pack Porosity (%)	Permeability (md)
20/40 SinterLite	3.40	0.724	47.1	333234
16/30 InterProp G2	3.08	1.035	41.2	476840

Proppant Permeability Plot

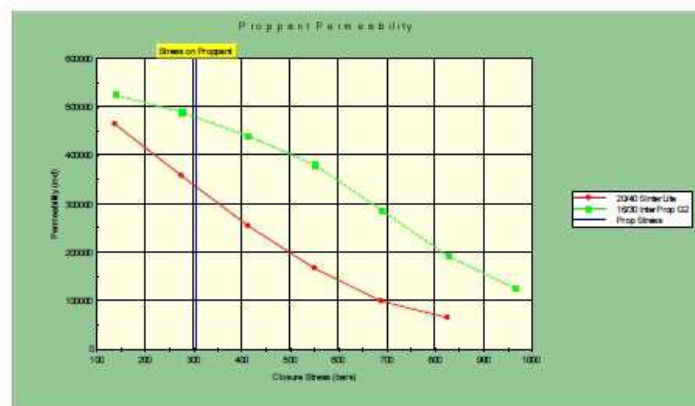


Fig. 15: Proppant Data Report

Calculated Fc was equal to 863 mDm

Max Hyd Frac Half-Length	190.0 m	EOJ Net Pressure	85 bars
Propped Frac Half-Length	189.9 m	Efficiency	0.271
EOJ Hyd Frac Half-Length	135.7 m	Effective Conductivity	895 md.m
EOJ Hyd Height at Well	86.7 m	Average Gel Concentration	123.6 kg/m3
EOJ Hyd Width at Well	9.7 mm	Effective Fcd	5.8
Propped Width at Well	3.2 mm	Max Surface Pressure	541 bars
Average Propped Width	3.2 mm	Estimated Closure Time	107.1 min

Segment		Average Property: EOJ				Average Property: ACL				
Segment From m	Segment To m	Slurry Height m	Pack Height m	Prop. Conc. kgPA	Propped Width mm	Propped Height m	Prop. Conc. kg/m2	Gel Conc. kg/m3	Conductivity md.m	
0.0	47.5	66.3	0.0	1089	3.9	55.6	6.61	99.8	1013	
47.5	94.9	71.9	0.0	1086	3.9	71.5	6.61	79.2	941	
94.9	142.4	60.5	0.0	1665	4.2	60.2	7.28	60.3	925	
142.4	189.9	19.2	0.0	408	1.2	35.1	2.23	251.8	266	

Fig. 16: Post Job Report

Field Example

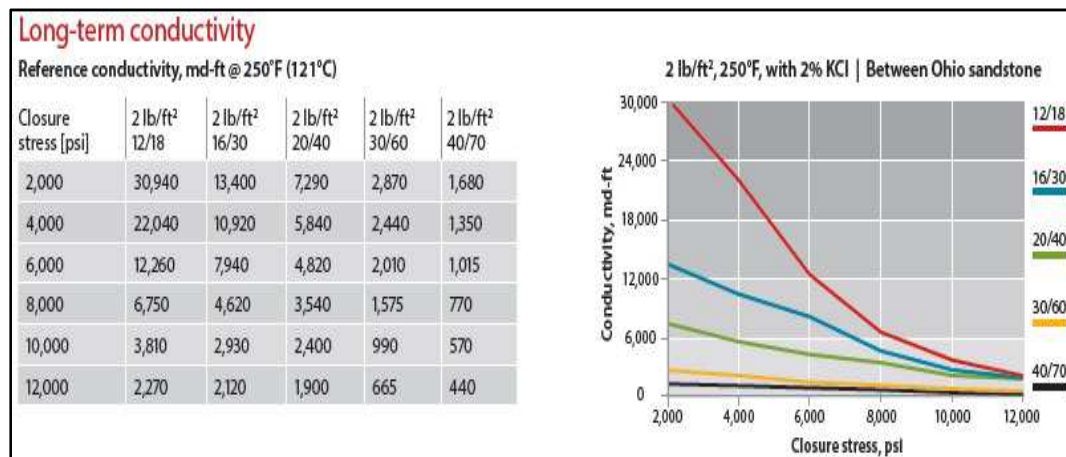


Fig. 17: Conductivity from technical data sheet

Closure Pressure [psi]	12/18[mD·ft]	16/30 [mD·ft]	20/40 [mD·ft]	30/60 [mD·ft]	40/70 [mD·ft]
2 000	5 961	2 963	1 528	694	355
4 000	5 279	2 625	1 353	615	315
6 000	4 733	2 353	1 214	552	282
8 000	4 265	2 121	1 094	498	255
10 000	3 851	1 916	988	450	230
12 000	3 479	1 731	893	406	208

Table. 1: Calculated conductivity based on technical data sheet

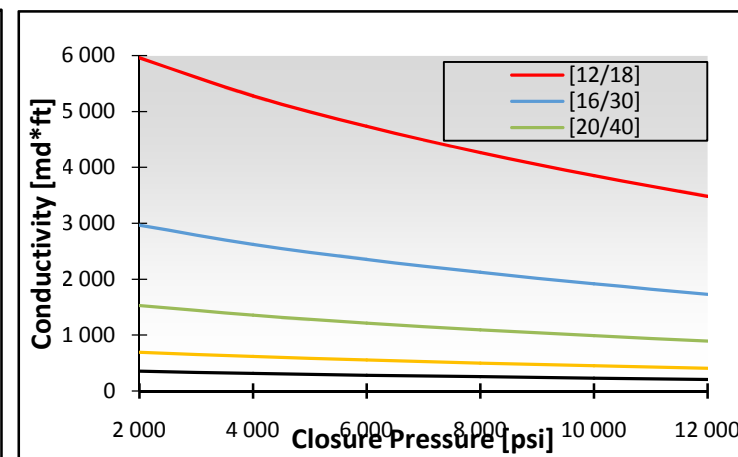


Fig. 18: Calculated conductivity based on technical data sheet

Conclusion

- Proppant embedment, deformation, change of fracture aperture, fracture conductivity can be computed with the analytical model
- Assumptions mean limitations (sphericity, elastic behavior etc.)
- Impact of all the influencing parameters can be determined (proppant size, closure pressure, Young's modulus of proppant and formation etc.)
- Combined the model with UFD and others, a kind of technical optimization of proppant selection can be executed
- Comparison can be made between F_c values from technical data sheets and calculated ones

Nomenclature

Symbol	Denomination	Dimension
α	change in fracture aperture	[mm]
θ	proppant deformation	[mm]
ν_1	Poisson's ratio of proppant	[-]
ν_2	Poisson's ratio of formation	[-]
Φ	porosity	[-]
τ	pore tortousity	[-]
D_1	diameter of proppant	[mm]
D_2	thickness of the formation	[mm]
E_1	elastic modulus of proppant	[Mpa]
E_2	elastic modulus of the formation	[MPa]
H	proppant embedment	[mm]
K	distance coefficient	[-]
p	closure pressure	[MPa]
r	radius of pore throat	[μ m]

Köszönöm megtisztelő figyelmüket!