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Optimization of HJC material parameters of rock splitting mechanism by dynamics simulation

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ABSTRACT

To understand the tensile fracturing mechanism of rock cutting-splitting method, the fracture toughness of rock should be defined. We performed 3-point bending tests for 2 types of rocks. Then, the LS-Dyna code was adopted to simulate the 3-point bending tests and the tensile fracturing procedures of rock. The sample rock was modeled using the HJC (Holmquist-Johnson-Cook) rock material model, and the key parameters were selected by sensitivity analysis and then optimized to precisely describe the mechanism. Finally, the suggested material model and the simulation results were validated with the 3-point bending experiment results. The proposed 3 key parameters (e.g. *PL*, *k*1, and *evol*) can successfully describe the tensile fracturing process of rock model.

1. INTRODUCTION

The application of rock blasting method in urban area is gradually regulated because the noises and vibration induce inconvenience to civilians. To minimize the disadvantages of the blasting method, some methods producing less vibration (e.g. smooth blasting, drilling-splitting, water jetting method, etc.) has been used in urban site. However, these methods are suffering from the low working efficiency and poor excavation rate when encountering the hard rock.

The study is developing a new cutting-splitting method which is for rapid excavation rate for hard rocks. The procedure is that cutting rock at a certain depth by a rock saw, and then splitting the rock into two blocks by inserting a chisel into the crevice. The key

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mechanism of the method is tensile fracture propagation on the basement of rock blocks. To understand the fracture mechanism of rock, the fracture toughness (mode I) of each rock should be determined. 3-point bending tests were performed for two strength rock classes (i.e., medium and hard strength). From the results, fracture toughness (mode I) values of the samples were obtained.

Then, the LS-Dyna code was used to simulate the tensile fracturing procedures during 3-point bending tests. HJC (Holmquist-Johnson-Cook) material model (Holmquist et al., 1993) was adopted. The model has many input parameters which are very hard to be defined with limited numbers of laboratory experiments. We performed sensitivity analysis to filter out the important parameters before the main simulations. After selecting key parameters, a series of 3 point bending simulations were carried out. The simulation data were compared to the experimental results by the optimization method. After the procedure, we suggested the optimum values for the two classes of rocks. This can help solving tensile fracturing process in rock splitting method to the future study.

2. Methodology

2.1 3-point bending test

The 3-point bending test devices were designed according to the suggested method (ISRM, 1988). These devices consist of a cylindrical rock specimen which is supported by two fixed rollers near the end of its length (Fig. 1). Also, the rock specimen is set-up horizontally through a loading roller located on the center of the rock specimen.

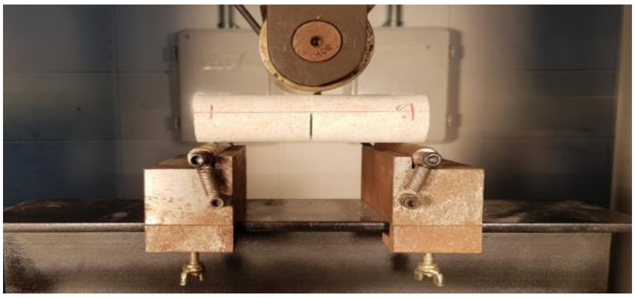


Fig. 1 The setup on the 3-point bending tests.

2.2 Dynamic code (Ls-dyna)

The fracture toughness test of 3-point bending is a quasi-static test. In order to solve the propagation process of tensile crack, it is necessary to calculate velocity, strain rate and stress as a function of time and position. We used LS-DYNA code (Livermore, 2014) to simulate the 3-point bending test of rock specimen.

2.3 HJC material model

The LS-Dyna code was used to simulate the tensile fracturing procedures during 3-point bending tests. HJC (Holmquist-Johnson-Cook) material model was adopted. The model was originally presented by Holmquist et al. (1993) with the purpose of developing a concrete model for impact computations where the material experiences large strains, high strain rates and high pressures (Polanco et al., 2008).

2.4 Optimization method

We adopted the evolutionary algorithm (EA) proposed by Jeong et al. (2005) for enhancing efficiency. They produced offspring by mixing genes of different chromosomes (an intermediate tendency recombination) and sometimes by randomly changing (mutation) some genes of the chromosomes. Then they deterministically selected the best chromosomes for the next generation. For efficient design optimization, a commercial software, PIAnO (Process Integration, Automation and Optimization) (PIDOTECH Inc., 2015) was used to integrate and optimize the simulation results to experimental data. A summary of the optimization procedure is shown in Fig. 2.

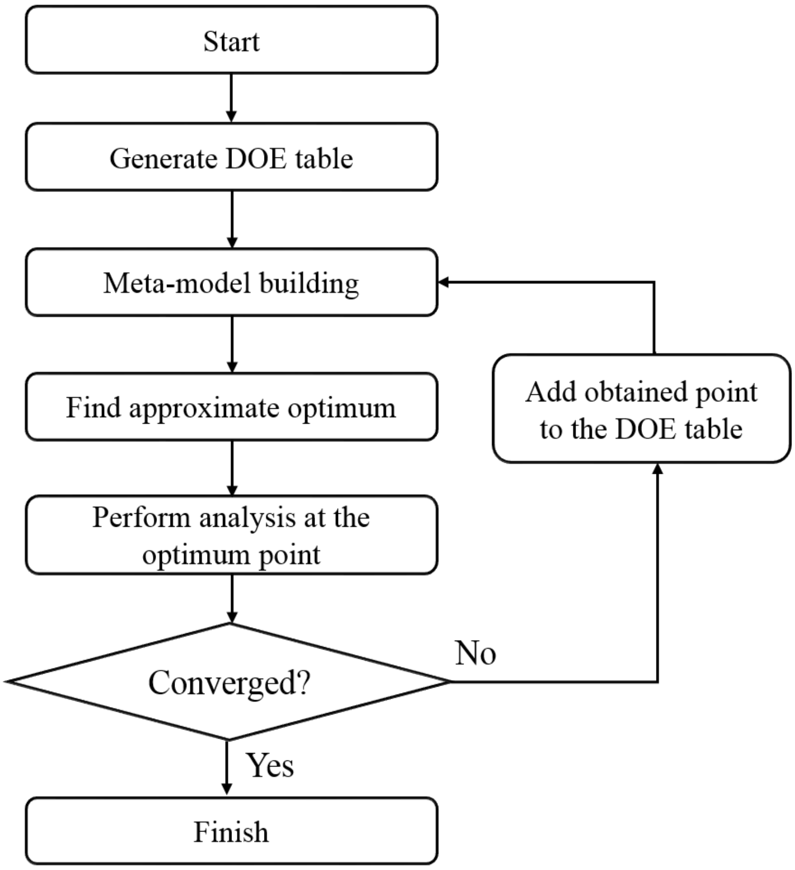


Fig. 1 Computational procedure of progressive meta-model based optimization.

2.5 Design of experiment (DOE) of 3-point bending tests

To simulate the fracture propagation of rock with HJC material model, we should define each value of 23 parameters for Ls-dyna code. Though 10 parameters can be obtained from static lab-scale test.

We have investigated the range of the parameters adopted in the previous studies (Holmquist et al., 1993; Polanco et al., 2008; Bu Changgen et al., 2009; Fang et al., 2014; Li and Shi, 2016).

Table 1. Upper and lower level of 13 parameters in HJC material model.

Design variables	Lower (1)	Middle (2)	Upper (3)
Normalized cohesive strength (*A*)	0.3	0.65	1
Normalized pressure hardening (*B*)	1.23	1.865	2.5
Strain rate coefficient (*C*)	0.0045	0.0071	0.0097
Pressure hardening exponent (*N*)	0.025	0.4575	0.89
Plastic strain before fracture (*EFMIN*)	0.004	0.007	0.01
Normalized maximum strength (*SFMAX*)	7	13.5	20
Locking pressure (*PL*)	0.8	1.65	2.5
Locking volumetric strain (*UL*)	0.012	0.196	0.38
Damage constant (*D*1)	0.01	0.028	0.046
Pressure constant (*k*1)	3.1	44.05	85
Pressure constant (*k*2)	-171	-73	25
Pressure constant (*k*3)	8.4	297.2	550
Volumetric erosion (*evol*)	0.001	0.0055	0.01

Table 2. DOE of 13 parameters for the simulations.

Exp. No	*A*	*B*	*C*	*N*	*EFMIN*	*SFMAX*	*PL*	*UL*	*D*1	*k*1	*k*2	*k*3	*evol*
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3

15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

Table 1 lists the lower and upper boundary values. The DOE of 13 parameters were made by three level L_{27} (3^{13}) orthogonal array. An orthogonal array of the DOE is listed in Table 2 based on the defined design level. The effect of the chosen parameters on the tensile fracture propagation is then evaluated by statistical analysis using the software by Minitab Inc. (2015).

2.6 Dynamic simulations

The 3-point bending simulation was performed according to the level combinations shown in Table 2. The finite element model used in the 3-point bending simulations is shown in Fig. 3. The dimension of the chevron bend specimen follows the suggested method (ISRM, 1988; KSRM, 2008), with the length and V-notch of the cylindrical rock specimen 150.4 mm and 1 mm, respectively. Then a series of simulations were carried out (Fig. 4) and the results were obtained (Fig. 5). The effect of each parameter on the tensile failure of the rock was evaluated using analysis of variance (ANOVA).

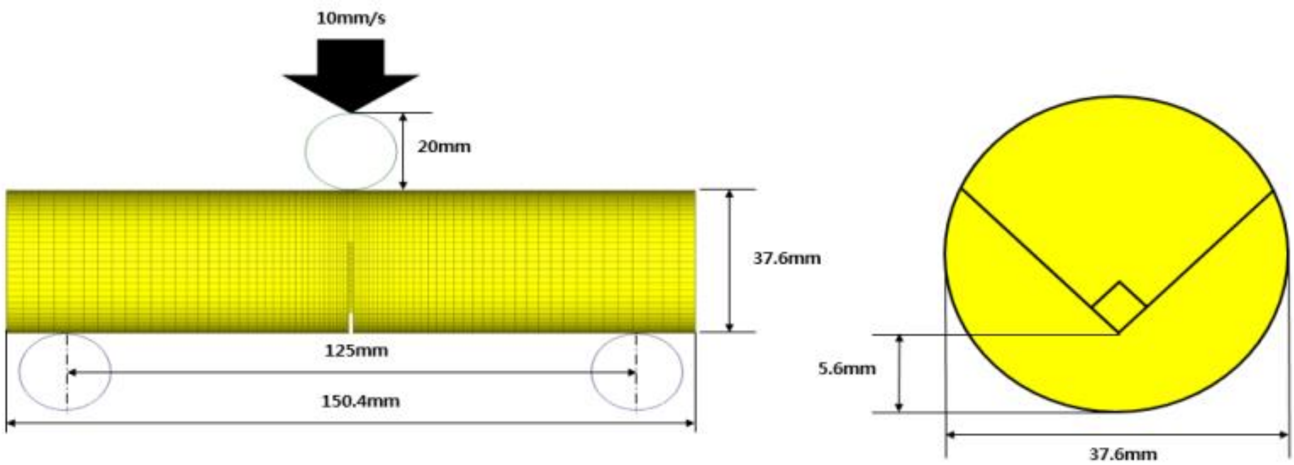


Fig. 3. Numerical model of chevron bend specimen

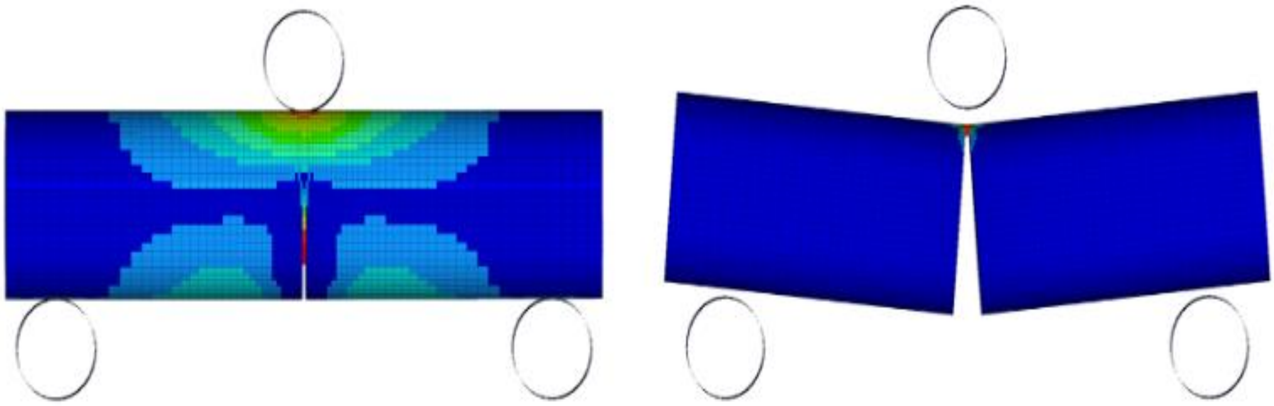


Fig. 4. Simulation result of 3-point bending test.

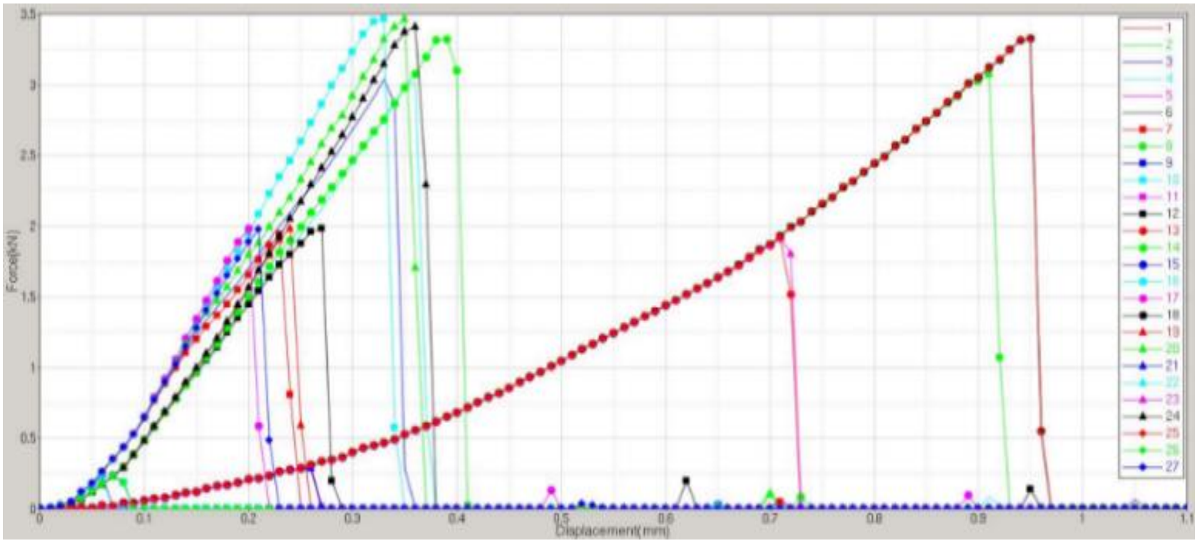


Fig. 5. Simulation results: force-displacement curves of 27 cases.

2.7 Sensitivity analysis

For the sensitivity analysis, screening method was utilized to filter out some important design parameters influencing the tensile failure in the simulation. The input design variables are 13 parameters of HJC material model and three output parameters are set to the slope of the force-penetration curve (k), the maximum force (F_{max}) and penetration (d_{max}) obtained from the 3-point bending tests. Table 2 lists the combinations of design parameters used in the orthogonal array for the 27 repetitions of the simulation. The contribution ratios of the design parameters extracted via screening method are listed in Table 3. The design factors *PL*, *k*1, and *evol* are significantly associated with the effects of the tensile fracture (95% significance level), thus influencing the tensile fracture, whereas parameters *A*, *B*, *C*, *N*, *EFMIN*, *SFMAX*, *UL*, *D*1, *k*2 and *k*3 are not. The pressure constants *k*2 and *k*3 in a tensile fracture has been reported not to contribution to the rock fracture effects (Holmquist et al., 1993).

Table 3. Contribution ratio of configuration variable for tensile fracture of HJC rock model.

Parameters	Contributions		
	F_{max}	d_{max}	k
A	1.2%	0.9%	0.6%
B	0.7%	3.6%	2.7%
C	0.4%	0.8%	0.1%
N	0.4%	0.9%	0.0%
EFMIN	0.5%	0.8%	0.1%
SFMAX	0.6%	0.8%	0.2%
PL	0.5%	4.7%	3.7%
UL	0.3%	1.2%	0.2%
*D*1	0.4%	0.7%	0.2%
*K*1	0.5%	43.0%	54.2%
*K*2	0.3%	0.6%	0.2%
*K*3	0.4%	0.6%	0.2%
evol	93.7%	41.4%	37.7%
Total	100.0%	100.0%	100.0%

The three parameters (*PL*, *k*1, and *evol*) were finally selected with a contribution rate of over 4%, and these were used to optimize the fitting of rock fracture toughness via the Kriging meta-model (Kleijnen JPC, 2009) and evolutionary algorithm.

2.8 Optimization procedure

The orthogonal array of the DOE and the Kriging meta-model were introduced to fit the selected three parameters to precisely describe the 3-point bending test. For that optimization process, a meta-model with evolutionary algorithm (Deb et al., 2009) was generated by the results of a 3-point bending simulations. An optimization problem for design of rock fracture toughness is formulated considering design requirements and design variables explained in Eq. (1).

- Find: *PL*, *k1* and *evol*
- To minimize error (*O*1): $\frac{\left|F_{\max}^{\exp} - F_{\max}^{sim}\right|}{F_{\max}^{\exp}} \leq 1\%$ (1)
- Constraint (*G*1): $\frac{\left|d_{\max}^{\exp} - d_{\max}^{sim}\right|}{d_{\max}^{\exp}} \leq 1\%$ (2)

Table 4 shows the results of the optimal levels of the HJC parameters derived for high strength rock. As shown in Table 4, the required design specifications and constraints were satisfied after 19th iterations.

Table 4. Convergence results of parameter for fracture toughness of high strength rock.

Opt. No.	*PL*	*k*1	*evol*	*G*1	*O*1
1	2.4884	83.39	0.0097	5.1%	234.2%
2	2.4978	3.47	0.0005	6.2%	60.9%
3	2.4903	3.74	0.0006	6.2%	59.2%
4	1.9726	4.10	0.0007	3.4%	52.4%
5	1.47719	4.14	0.0007	1.4%	48.9%
6	0.8318	4.14	0.0008	5.4%	43.9%
7	0.8314	5.40	0.0008	6.2%	42.7%
8	0.8309	7.82	0.0008	17.7%	40.2%
9	0.8453	4.64	0.0009	8.2%	35.4%
10	0.8765	5.07	0.0010	5.4%	32.0%
11	0.9803	5.09	0.0011	11.0%	22.9%
12	1.4796	8.00	0.0012	6.2%	19.9%
13	1.7118	8.02	0.0012	3.4%	15.3%
14	1.7881	8.20	0.0013	3.4%	13.9%
15	1.7994	8.04	0.0013	3.4%	14.6%
16	1.7890	8.17	0.0014	0.6%	11.8%
17	1.7534	8.32	0.00151	1.4%	7.3%
18	1.7245	8.40	0.00165	1.4%	6.3%
19	1.7181	8.50	0.00167	0.6%	0.4%

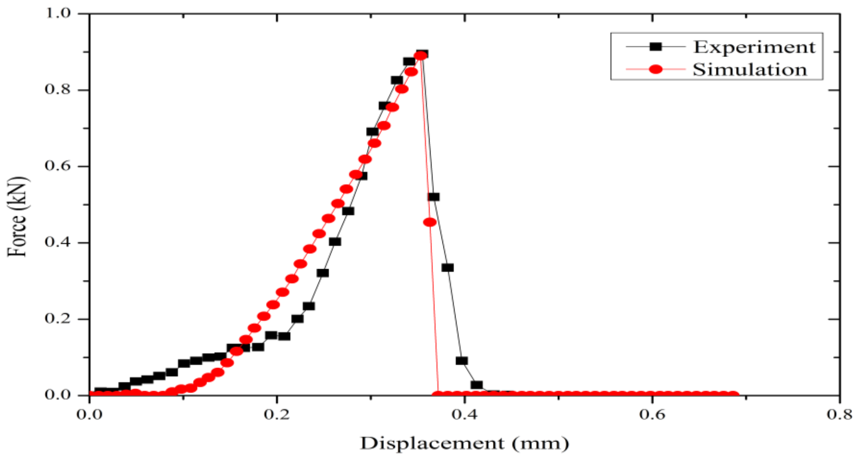
In the case of medium strength rock, the optimal solution could be observed through 18th iterations (Table 5).

Table 5. Convergence results of parameter for fracture toughness of medium strength rock.

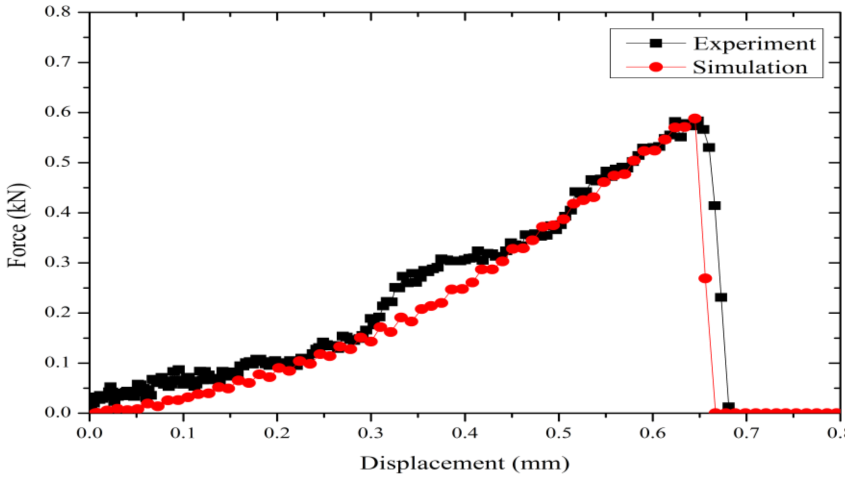
Opt. No.	*PL*	*k*1	*evol*	*G*1	*O*1
1	1.6118	4.51	0.00065	62.3%	40.8%
2	1.5557	4.63	0.00069	60.6%	35.0%
3	1.6213	0.66	0.00104	47.3%	3.1%
4	1.0958	1.73	0.00140	10.6%	18.4%
5	0.9745	1.70	0.00128	8.9%	21.6%

6	1.0425	3.64	0.00139	35.6%	21.3%
7	1.5552	0.66	0.00106	47.3%	2.9%
8	1.5555	0.50	0.00105	43.9%	2.9%
9	1.9498	1.17	0.00734	92.9%	253.7%
10	1.5557	0.65	0.00104	47.3%	3.3%
11	1.1995	1.17	0.00107	3.6%	0.9%
12	1.1904	1.25	0.00122	1.4%	13.4%
13	1.1995	1.15	0.00100	55.6%	10.5%
14	1.1025	1.17	0.00120	3.0%	10.1%
15	1.1025	1.17	0.00116	1.4%	9.1%
16	0.907	1.17	0.00117	1.4%	9.2%
17	0.819	1.16	0.00118	0.3%	0.8%
18	0.8320	1.16	0.00118	0.3%	0.7%

Fig. 6 shows the numerical simulation results of the HJC model parameters derived through the optimization process for two rock classes in comparison with the experimental results. Fig. 6 (a) to (b) show the simulations of tensile fracture toughness for hard rock, medium hard rock, respectively.



(a)



(b)

3. CONCLUSIONS

In order to analyze the tensile fracture mechanism of rocks, the 3-point bending tests and numerical simulations were performed. The tensile fracture characteristics of rocks were analyzed by the HJC material model and the Kriging meta-model and the evolution algorithm were adopted to fit and optimize the HJC parameters.

The 3 key parameters of the HJC material model, that significantly influence to the tensile fracture of rocks, were identified by the sensitivity analysis. Then, the levels of each parameter were proposed by processing optimization technique. Based on this result, the proposed three parameters (e.g. *PL*, *k*1, and *evol*) can successfully describe the tensile fracturing process of rock model.

The results of this study can be used as the fundamental research data for producing rock blocks using rock cutting and splitting methods. Future study will be required to analyze the tensile crack characteristics of various rock classes considering the real-scale rock mass.

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