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Model Test Study on the Transmission Law of Explosion Stress Wave in Rock Mass with Filling Joints

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Abstract

In order to study the propagation and attenuation law of explosive stress wave in rock mass with filling joints, and consider the influence of different crustal stress conditions, different strength mortar is used to simulate rock mass and joints, and the multi-functional simulation test device of geotechnical engineering is used to carry out explosive model test research, the influence characteristics of different in-situ stress conditions on the attenuation of explosive stress wave in rock mass with different thickness filling joints are analyzed, and obtain the transmission law of stress wave. The results show that: when the explosion stress wave propagates in the joined rock mass, the thicker the filling joint is, the greater the attenuation range of the stress wave energy and the samller the transmission coefficient; In-situ stress will change the attenuation of explosive stress wave in rock mass. With the increase of in-situ stress, the transmission coefficient of stress wave in intact rock mass and joined rock mass will increase. When the local stress is fixed, the transmission coefficient of stress wave in joined rock mass also increase gradually with the increase of explosion load.

Keywords

Explosive Mechanics; Stress Wave; Filling Joint; Crustal Stress; Model Test.

1. Introduction

The natural rock mass contains a large number of joint structural planes, which makes the rock mass have discontinuity and anisotropy, and is filled by rock particles to form filling joints under long-term geological action, which affects the mechanical properties of the whole rock mass. The phenomenon of transmission and reflection occurs when the stress wave generated by explosion passes through the structural plane of rock mass [1-2], especially when it passes through filling joints, multiple reflection occurs and leads to energy attenuation, resulting in the change of stress wave propagation in time and space.

The stress wave propagation process of underground rock mass engineering becomes more complicated due to the combined action of initial ground stress and explosion load. On the one hand, the combined action of ground stress and explosion load causes the rock mass properties to change, especially the structural plane morphology and filling properties, so that the incident Angle, dielectric material wave impedance and other parameters affecting stress wave propagation change. On the other hand, under the influence of different filling joints, the peak value of stress wave, the action time and other parameters will change, which will affect the rock mass and engineering structure under its continuous action. With the development of underground space exploitation, resource exploitation and various rock engineering, more and more attention has been paid to the study of the propagation attenuation law of explosive stress wave in filling jointed rock stratum.

At present, scholars at home and abroad mainly study the propagation of stress waves in rock mass containing filling joints based on the assumption of continuous displacement, and obtain certain conclusions [3-4]. Li[5-6] proposed a linear elastic thin layer model for packed joints,

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and derived the analytical solution of stress wave permeability and reflection coefficient in a single packed joint rock mass with theory. Li Xibing[7]comprehensively considered the wave impedance characteristics of the rock mass on both sides of the joint and the filling material itself, and derived the analytical solution of the transmission-reflection coefficient of stress waves passing through the filling joint by using the equivalent wave impedance method. Guo Wenwen [8] conducted an electrical test on the jointed rock mass model, analyzed the propagation law of explosion strain wave in jointed rock mass and the rock mass fracture form, and studied the blasting energy loss of jointed rock mass. Liu Tingting [9] used discrete element program Udec for numerical simulation to study the influence of the thickness, spacing and number of filling joints on the transmission coefficient of stress waves, and found that the influence of the number of joints on the transmission coefficient was related to the spacing of joints. Jin Jiefang et al. [10-11] studied the dynamic mechanical properties of rocks under the combined dynamic and static loading device, and the results showed that static loading would change the porosity or damage degree of rocks. Chen Xuefeng [12] carried out joint blasting model tests and optimized blasting parameters in field tests. Li Xinping [13] studied the permeability and reflection coefficients of intact rock mass and jointed rock mass respectively under different ground stress levels through model tests. He found that with the increase of ground stress, the attenuation of stress waves to jointed rock mass increased, in which the attenuation effect of rock materials on stress waves increased, while that caused by joints weakened. Liu Xin [14] used SHPB device with confining pressure chamber to impact intact rock specimens and specimens filled with cracks respectively, and found that confining pressure changes the wave attenuation effect of cracks by changing the porosity of fillings, and the wave attenuation effect of filled cracks decreases with the increase of confining pressure.

In conclusion, the current research on stress wave propagation in jointed rock mass is relatively comprehensive without considering the ground stress. When considering the action of ground stress, most of the research focuses on the mechanical properties of intact rock mass and stress wave propagation in jointed rock mass under the action of ground stress, and there are few research on stress wave propagation in jointed rock mass under the action of ground stress, and few test means. By carrying out explosion model tests, this paper studies the propagation and attenuation of explosion stress waves in rock mass with packed joints under different loading stress conditions, analyzes the influence of packed joint thickness on the attenuation of stress waves under different ground stresses, and obtains research conclusions that are closer to the actual state, which can provide references for rock mass engineering safety issues involving stress wave propagation.

2. Model Test

2.1. Test Equipment and Model Materials

(a) Side of test unit (b) Front side of test unit

Figure 1. Multifunctional simulation test device of geotechnical engineering

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In this test, a multifunctional simulation test device [15] of geotechnical engineering is used to conduct the test. A test model is made inside the device, and a uniform load is applied at the boundary to simulate the ground stress, which can be loaded up to 1.5MPa at maximum. The center of the model is coupled with the cylindrical detonating cable, through which the explosive stress wave is generated. The test device and the test model were placed horizontally, and the quasi-plane strain loading condition was adopted, as shown in Figure 1.

This test is aimed at the underground granite stratum in a mining area, and the joint filling material is dense sandstone. According to the similarity theory of model test, the Froude similarity theory was adopted, and the similarity ratio of related physical quantities was determined according to the test device and conditions, etc., among which, the stress similarity ratio between prototype and model was 10, the geometric similarity ratio was 8, and the density similarity ratio was 1.25. Cement mortar was used to simulate rock mass, and gypsum mortar was used to simulate filling joints. Model materials with appropriate strength were prepared according to the similarity ratio, and then test models were made, and the tests were started after maintenance until the properties were stable. The mechanical parameters of rock mass prototype and model materials are shown in Table 1.

Table 1. Mechanical parameters of rock mass and similar materials

material	Compressive Strength/ MPa	Tensile strength/MPa	Modulus of elasticity/ GPa	Density/ (g/cm^3)	Poisson's ratio
marble	46.7	5.7	14.9	2.3	0.26
Cement mortar	4.556	0.6	1.31	1.9	0.267
joints	18	-	8.3	1.6	-
Gypsum mortar	1.73	0.18	0.71	1.15	0.171

2.2. Model Design and Test Conditions

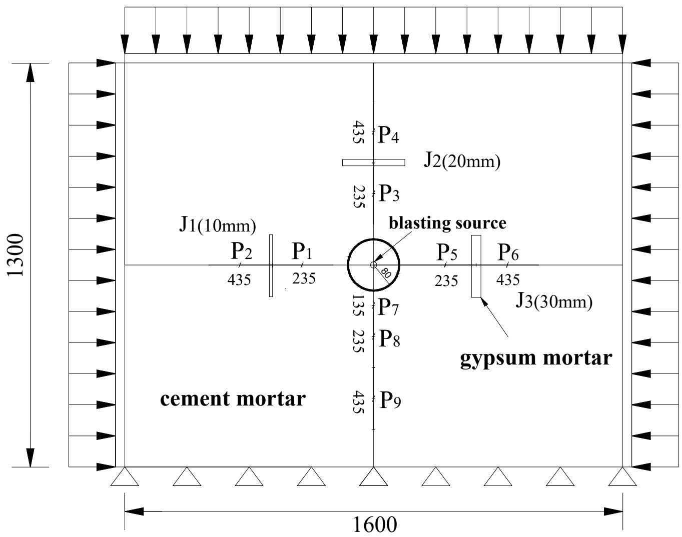

Figure 2. Schematic diagram of test design and measuring point layout

The test model size is 1.6m×1.3m×0.4m. For ease of comparison, filling joints of different thicknesses were set in three directions of each model, denoted as J_1, J_2 and J_3, with thicknesses of 1cm, 2cm and 3cm respectively. For this reason, four stress measuring lines are arranged in four directions of the model, three of which pass through the filling joints, and stress measuring points are set at the same positions before and after the joints. For comparison, the other measuring line is arranged in the direction without joint, and the measuring point position is

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the same as that of the other three directions. Meanwhile, stress measuring point P7 is added, 135mm away from the detonation source, as shown in Fig.2. A series of studies were carried out by adjusting the boundary loading (ground stress) and charge amount (explosion load). The boundary loading mode of the model was synchronous and uniform loading in all directions with the same pressure boost rate. After reaching the required load, the pressure was stabilized for 10min and then explosion loading was carried out. KD2009T series earth pressure sensors were used for stress measurement, and Dewesoft dynamic data acquisition system was used for data acquisition, with a sampling frequency of 400kHz. The schematic diagram of test design and measuring point layout is shown in Figure 2, and test conditions are shown in Table 2.

Table 2. Test condition

Test number	Charge /kg	Loading stress /MPa	Simulated ground stress /MPa
1	0.0144	0	0
2	0.0144	0.5	5
3	0.0144	1	10
4	0.0192	1	10
5	0.0240	1	10
6	0.0288	1	10

2.3. Test Results

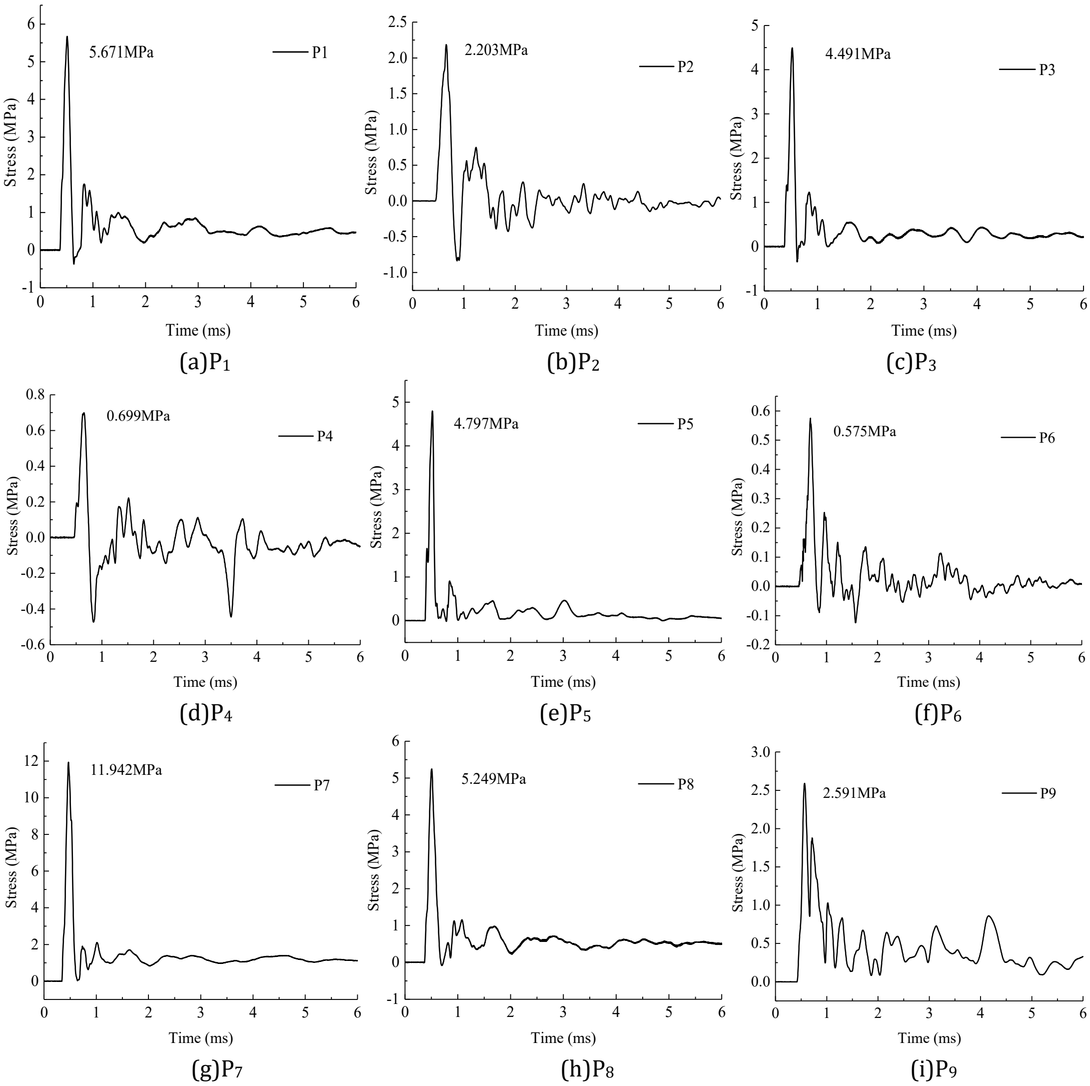
The stress waveform of each measuring point under the test condition 1 is shown in Figure 3. See Table 3 for the stress peaks of each measuring point in all test conditions.

Table 3. Peak stress of each measuring point in the test

Measuring point	Peak stress /MPa					
	1	2	3	4	5	6
P_1	5.671	6.975	7.463	7.439	7.846	8.643
P_2	2.203	2.844	3.163	3.210	3.55	4.018
P_3	4.491	6.383	6.528	7.249	8.054	8.310
P_4	0.699	1.223	1.297	1.522	1.939	2.232
P_5	4.797	5.839	6.510	7.520	7.776	8.137
P_6	0.575	0.736	0.871	1.066	1.231	1.447
P_7	11.942	15.694	18.01	22.369	27.689	32.548
P_8	5.249	5.578	5.315	5.855	6.275	7.231
P_9	2.591	2.916	3.528	4.493	4.746	5.447

According to the diagram of working condition 1, the stress peaks measured at the four measuring points P1, P3, P5 and P8 235mm away from the explosion source center are 5.671MPa, 4.491MPa, 4.797MPa and 5.249MPa, respectively. The difference between the stress peaks is small, indicating that the stress waves generated by the explosion propagate evenly in the model. The stress peaks measured at the measurement points P2, P4 and P6 after filling joints are 2.203MPa, 0.699MPa and 0.575MPa successively, indicating that the stress attenuation degree of stress wave is different when filling joints with different thickness. The thicker the joints, the smaller the stress of transmitted wave peak and the greater the attenuation value.

According to each working condition, the explosion test was carried out to obtain the stress-time waveform of each measuring point, and the corresponding data of stress peak and proportional distance were obtained. In this test, the rock mass between the stress measurement points at the head and tail in the direction of stress wave propagation is taken as the research object. According to the calculation method of transmission coefficient in literature [13], Transmission coefficient = stress peak value of measuring point after joint/stress peak value of measuring point before joint. In this test, P_1, P_3 and P_5 were respectively taken as incident waves and P_2, P_4 and P_6 as transmitted waves to calculate the transmission coefficients of stress wave propagation of different joints in various working conditions, so as to carry out the analysis of the propagation law of explosive stress wave in packed joint rock mass. The transmission coefficient is calculated as follows: $M_{J1}=P_2/P_1$, $M_{J2}=P_4/P_3$, $MJ3=P_6/P_5$. In order to facilitate comparative analysis, a measuring point at the same position on the measuring line 4 is selected to calculate the case without joint, which is still defined as "transmission coefficient" for comparison, and expressed as: $M_{J4}=P_9/P_8$.



(a)P_1 (b)P_2 (c)P_3
(d)P_4 (e)P_5 (f)P_6
(g)P_7 (h)P_8 (i)P_9

Figure 3. Stress waveform of each measuring point in T1 working condition

3. Test Analysis

3.1. Stress Wave Propagation in Intact Rock Mass

The propagation attenuation of explosive stress wave parameters in rock mass is mainly related to the ratio of the propagation distance to the cubic root of explosive charge, which is the proportional distance. The explosion stress wave parameters decay exponentially along with the proportional distance, and the attenuation formula is:

$$P=A(D/Q^{1/3})^{-B} \quad (1)$$

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Where, P is the stress value (MPa); D is the distance from the explosion source center (m); Q is the dosage (kg); A is the attenuation coefficient; B is the attenuation exponent.

The attenuation curve of explosion stress value can be obtained by fitting the stress peak values of stress measuring points P7, P8 and P9 and their proportional distances on measuring line 4. Since the measuring points of each incident wave (P1, P3, P5) are located in front of joints, they can also be fitted together as measuring points in intact rock mass. Finally, the attenuation curve of stress wave in intact rock mass under each working condition is obtained. The formula of attenuation curve under various working conditions is obtained. The coefficient A and attenuation index B in the formula are shown in Table 4.

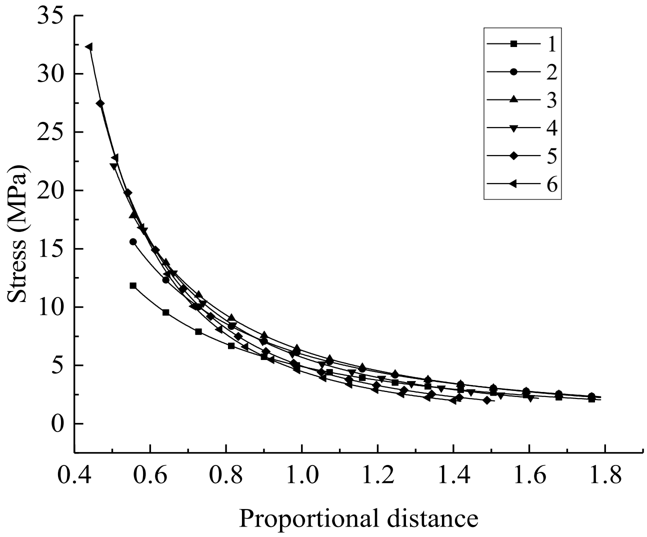

Figure 4. Fitting curve of stress attenuation in each working condition

Table 4. Parameters of stress attenuation fitting formula in each working condition

Working condition	*A*	*B*	R^2
1	4.903	1.497	0.972
2	5.963	1.632	0.979
3	6.283	1.771	0.960
4	5.695	1.981	0.955
5	4.944	2.258	0.964
6	4.484	2.408	0.966

The attenuation of explosion stress wave with propagation distance in rock mass is mainly related to the material properties of rock mass. Static load may change the porosity of rock mass or cause damage to rock mass. In working conditions 1, 2 and 3, the explosion load remains unchanged, while the loading stress is 0MPa, 0.5MPa and 1MPa respectively. It can be seen from the table that with the increase of loading stress, the coefficient A in the attenuation formula increases gradually, and the index B also increases, and the attenuation curve changes obviously. The loading stress in working conditions 3-6 is all 1MPa, and the rock mass properties do not change when the explosion load is increased. Within the test error range, it can be seen from FIG. 4 that the stress attenuation curves in working conditions 3-6 are nearly identical, and the charging amount has little influence on the propagation and attenuation of stress waves in intact rock mass.

The static load applied to rock mass will change the physical and mechanical properties of rock mass, so that the attenuation law of stress wave in rock mass changes. In the test condition 1-3,

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with the increase of loading stress, the coefficient A and attenuation index B in the stress attenuation formula gradually increase, and the attenuation curve changes obviously.

3.2. Transmission Law of Stress Wave in Packed Jointed Rock Mass

The transmission coefficients of stress waves through intact rock mass and jointed rock mass with different thicknesses under different working conditions are shown in Table 5, and the changes of transmission coefficients under different working conditions are shown in Figure 5. On the whole, the transmission coefficient of the unjointed line is greater than that of the jointed line, indicating that the joint can increase the attenuation amplitude of stress wave compared with that of the intact rock mass. At the same time, it is found that the thickness of the joint has a significant effect on the transmission coefficient. Under the same working condition, the thicker the filling joints in the rock mass are, the smaller the measured transmission coefficient is, and the larger the attenuation range of the stress wave is. It indicates that the thicker the filling joints are, the stronger the attenuation effect of the stress wave energy is, and the lower the energy transfer efficiency is.

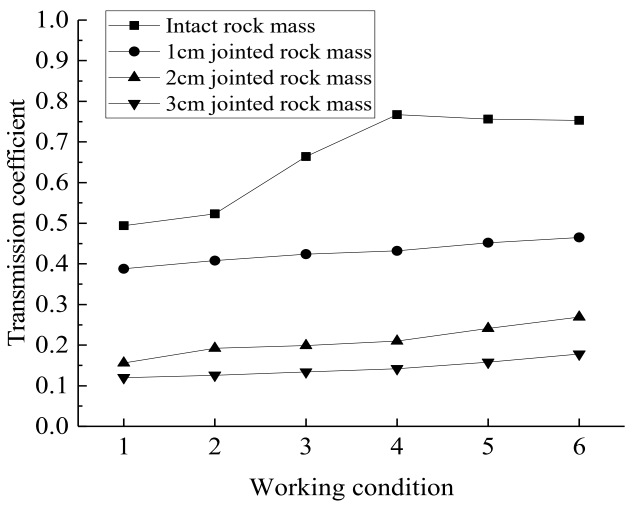

Figure 5. Transmission coefficient of rock mass with joints of different thickness under various working conditions

Table 5. Transmission coefficient of rock mass with joints of different thickness under various working conditions

Joint thickness /cm	Transmission coefficient					
	1	2	3	4	5	6
0	0.494	0.523	0.664	0.767	0.756	0.753
1	0.388	0.408	0.424	0.432	0.452	0.465
2	0.156	0.192	0.199	0.210	0.241	0.269
3	0.120	0.126	0.134	0.142	0.158	0.178

3.3. Influence of Ground Stress on Stress Wave Propagation

It can be seen from the analysis in 2.1 that the ground stress will affect the attenuation law of stress waves in intact rock mass, and the ground stress will affect the attenuation of stress waves by changing the properties of rock mass. As can be seen from Figure 6, with the increase of simulated ground stress, the stress attenuation curve of working conditions 1 to 3 changes from slow to steep. The coefficients A in the attenuation fitting formula are 4.903, 5.963 and 6.283 respectively, increasing successively, and the attenuation index B is 1.497, 1.632 and 1.771 respectively, which also increase successively. It can be seen that the greater the ground stress is, the greater the stress attenuation rate from near to far when the stress wave propagates through the rock mass.

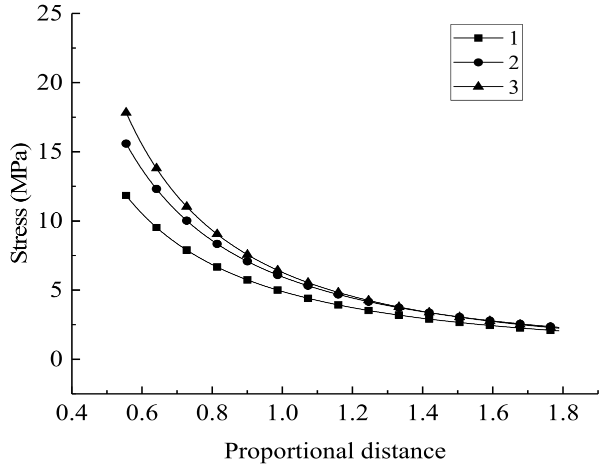

Figure 6. Fitting cures of stress attenuation under different loading stresses

FIG. 7 shows the variation trend of the transmission coefficient of each measured line under different loading stresses. When the loading amount is fixed, the transmission coefficient of stress wave in intact rock mass and jointed rock mass increases with the increase of loading stress. For intact rock mass, when the test loading stress is 0MPa, 0.5MPa and 1MPa, the transmission coefficient of intact rock mass is 0.494, 0.523 and 0.664, and the growth rate is 5.87% and 26.96%, respectively. When the loading stress increases from 0.5MPa to 1MPa, the transmission coefficient increases significantly. For jointed rock mass, the transmission coefficients of stress wave passing through jointed rock mass with 1cm thickness are 0.388, 0.408 and 0.424, and the growth rates are 5.15% and 3.92%. The transmission coefficients of stress wave passing through rock mass with 2cm thick filling joints are 0.156, 0.192, 0.199, and the growth rates are 23.08% and 3.65%, respectively. The transmission coefficients of stress waves passing through the rock mass with 3cm thick filling joints are 0.120, 0.126 and 0.134, respectively, and the transmission coefficients are 5% and 6.35% respectively.

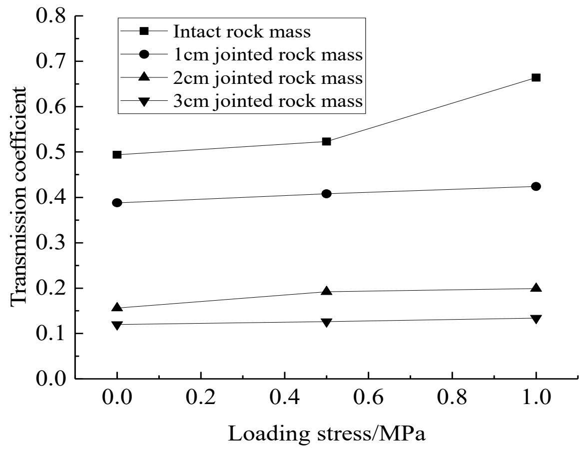

Figure 7. Transmission coefficient of rock mass with joints of different thickness under different loading stress

3.4. Influence of Charging Amount on Transmission Coefficient of Jointed Rock Mass

The change of transmission coefficient of each line under different working conditions is shown in Figure 8. The loading stress of working conditions 3-6 is 1MPa, and the charging amount is 0.0144kg, 0.0192kg, 0.024kg and 0.0288kg, respectively. With the increase of charge, the change trend of non-jointed measurement lines was not obvious, and the transmission coefficient of jointed measurement lines increased in different degrees. According to Table 6, with the increase of charge, the transmission coefficient of non-jointed measured line is 0.664, 0.767, 0.756 and 0.753. In this test, the transmission coefficient of intact rock mass is less affected by explosion load. When the stress wave passes through the rock mass with 1cm thick filling joints, the transmission coefficients are 0.424, 0.432, 0.452 and 0.465, and the growth rates of the transmission coefficients are 1.89%, 4.63% and 2.88%. The transmission coefficients of the stress wave passing through the rock mass with 2cm thick filling joints are 0.199, 0.210, 0.241, 0.269, and the growth rates of the transmission coefficients are 5.53%, 14.76%, 11.62%. The transmission coefficients of the stress wave passing through the rock mass with 3cm thick filling joints are 0.134, 0.142, 0.158, 0.178, and the growth rates of the transmission coefficients are 5.97%, 11.27%, 12.66%. With the increase of explosion load, the transmission coefficient of jointed rock mass also increases. It can be seen from the broken line figure that the thicker the joints, the smaller the transmission coefficient, the transmission coefficient of 2cm thick filling joints and 3cm thick filling joints is much less than that of 1cm filling joints, indicating that 2cm and 3cm thick filling joints have better attenuation effect on stress waves than 1cm thick filling joints, and the difference between the transmission coefficients of 2cm joint and 3cm joint measuring lines is small. It shows that the energy barrier effect of the two kinds of joints is similar, which can provide reference for the safety protection of jointed rock mass explosion.

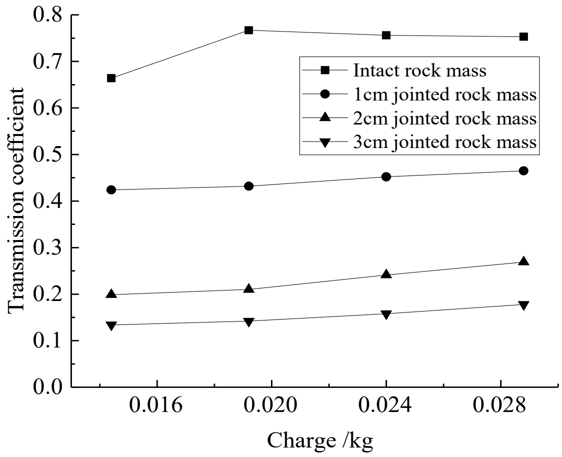

Figure 8. Transmission coefficient of rock mass with joints of different thickness under different explosive quantities

4. Conclusion

1) Ground stress will affect the attenuation of explosion stress wave in intact rock mass. With the increase of ground stress, both the coefficient and attenuation index of stress attenuation fitting formula will gradually increase, significantly affecting the attenuation law of stress wave.

2) Compared with intact rock mass, the stress value of stress waves after filling joints attenuates obviously, and the thickness of joints has a significant influence on the transmission coefficient. Under each working condition, the thicker the filling joints in rock mass are, the smaller the transmission coefficient is, the greater the attenuation range of stress waves is, and the better the barrier effect on energy is.

3) With the increase of ground stress, the transmission coefficient of stress wave in intact rock mass and rock mass with filling joints of different thicknesses will increase, and the attenuation range of stress value will decrease. When the ground stress is constant, the transmission coefficient of stress wave in rock mass with filling joints of different thicknesses will also increase with the increase of charge amount (explosion load).

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