A Study on the Mechanism of the Millisecond Delay Blasting

By

Ichiro ITO, Yoshikazu WAKAZONO, Yuzo FUJINAKA
and Makoto TERADA

Department of Mining

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1. Introduction

The millisecond delay blasting has been introduced into our country after the World War II and it is now used effectively at various metalliferous and non-metalliferous mines. But it is not yet made clear why the millisecond delay blasting is advantageous and more effective compared with the other methods of blasting such as the simultaneous shot-firing or the ordinary delay blasting with the delay interval of approximately one second. Some opinions have been proposed to explain this fact and among them a paper written by Dr. Kumao Hino[1] is considered most worthy of referring.

The authors recently carried out a few experimental researches concerning the mechanism of the rock blasting. The purposes of these experiments were to consider the mechanism of the millisecond delay blasting through the measurements of the following phenomena:

(1) the characteristics of the strain induced in rocks in the case of the millisecond delay blasting,

(2) the period of the rock burst; in other words, how much time is required to break the rocks in the crushing zone after explosives are detonated,

(3) the period of producing a crater; in other words, how much time elapses before a complete crater is produced after explosives are detonated.

In this paper, the authors shall report of the results obtained in the above experiments and also discuss about the results of consideration on the mechanism of the millisecond delay blasting.

2. Strains induced in Rocks in the Case of the Millisecond Delay Blasting

The electric resistance strain gauges, amplifiers, and an electromagnetic oscillograph were used to measure strains induced in rocks at the time of blasting. For the electric resistance strain gauges, mainly the Carlson type gauges were used and the paper type gauges were also used for the purpose of comparison. The amplifier was composed of the ordinary *R–C* coupled circuit, and the anode current of the power amplifying tube was passed directly through the vibrator of the oscillograph to avoid undesirable influences caused by the employment of the output transformer. In these experiments, two amplifiers of exactly the same characteristics were operated and attached to the oscillograph vibrators to simultaneously record both the axial and radial strains. The average gain of these amplifiers was 85 db, and the deviation in the range from 50 cps to 4,000 cps was less than ± 3 db.

All the records were taken by the electromagnetic oscillograph, Yokokawa Electric Works Model N-6, and the vibrators installed were the type A (natural frequency: 6,000 cps, sensitivity: 2 mA/mm).

These experiments were carried out in the underground of the Kamioka mine in Japan. The rock blasted was the hedenbergite with lead and zinc ores. For reference, the results of testing the principal physical properties of the above rock and the velocities of propagation of the longitudinal elastic waves, measured by means of the ultrasonic impulse transmission, are shown in Table 1.

Table 1. Physical properties of hedenbergite, Kamioka mine.

Number of sample	Length (cm)	Diameter (cm)	Sectional area (cm^2)	Kind of test*	Breaking load (kg)	Poisson's ratio	Young's modulus (kg/cm^2)	Velocity of propagation of longitudinal wave (m/sec)
1	4.93	2.10	3.462	Tension	520			3,040
2	5.17	2.15	3.597	Tension	760			3,670
3	4.84	2.17	3.696	Compression	2,500			4,240
4	5.07	2.13	3.561	Compression	1,560	0.17	25×10^4	4,220
5	4.86	2.10	3.461	Compression	1,200	0.17	14×10^4	3,110
6	4.56	2.09	3.429	Tension	450			2,870

* Tensile strength was measured by cylinder test.

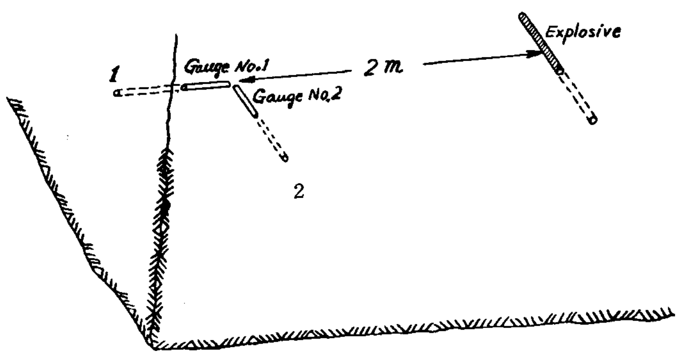

Fig. 1. Arrangement of boreholes in the single shot-firing.

At first, the measurements of strains induced in rocks in the case of the single shot-firing were performed. Two boreholes (Nos. 1 and 2) having three free faces, as shown in Fig. 1, were drilled in the rocks in the direction so as to be at right angle to each other and to intersect almost at a point. Gauge No. 1 and No. 2 were placed at the bottom of the respective holes. Another borehole in which the explosives were to be charged was drilled at a distance about 2 meters from the above holes. Therefore, the axial strain could be caught by the gauge No. 1 and the radial strain, which was perpendicular to the former one, could be caught by the gauge No. 2.

Shinkiri dynamite (an ammonia gelatin dynamite), Murasaki Carlit (a perchlorate explosive mixture), and Shōan dynamite (an ammonia permissible) were chosen to study the relation between the differences in the magnitude of strains caused by different strength of explosives, while Shinkiri dynamite alone was used to compare the differences in the magnitude of strains caused by the differences in the quantity of explosives.

The experimental results obtained are shown in Table 2. The measured frequencies of the strain waves in rocks ranged from 800 cps to 2,150 cps, and the velocity of propagation of the strain waves was 3,200 m/sec on the average. It is considered in general that the measured duration of the strain wave differs accordingly with the

Table 2. Strains in hedenbergite in the case of single shot-firing.

Number of gauge	1	2	1	2	1	2	1	2	1	2
Kind of strain	axial	radial	axial	radial	axial	radial	axial	radial	axial	radial
Kind and quantity of explosives (grammes)	Shinkiri dynamite 225		Murasaki carlit 225		Shōan dynamite 225		Shinkiri dynamite 112.5		Shinkiri dynamite 450	
Distance from the shot point (meters)	2.0	1.7	2.0	1.9	2.0	1.9	2.0	1.8	2.0	1.7
Principal frequency of strain wave (cps)	1,020	1,090	1,000	—	800	870	1,700	1,500	1,600	2,150
Velocity of propagation of strain wave (m/sec)	4,700	5,600	3,000	3,300	3,100	3,600	2,200	2,400	2,000	2,000
Duration of strain wave (milliseconds)	2.7	2.7	3.1	3.1	3.2	3.0	3.4	3.4	2.6	2.6
Magnitude of strain ($\times 10^6$)	30.5	15.8	36.2	10.9	13.7	3.5	19.2	8.3	52.4	26.6

sensitivity of the measuring apparatus used and the characteristics of the shot points. However, in these experiments, the results obtained showed 3 milliseconds as the average duration, although somewhat slight deviations in each record were recognized. As a matter of course, some considerable differences in the magnitude of strains were recorded depending upon the differences in the strength and quantity of the explosive used as shown in Table 2. Moreover, the magnitudes of the radial strains were from a half to a quarter of those of the axial strains.

Next, experiments were performed for the purpose of determining how the superposition of the strains, which are induced in rocks due to the subsequent shots of the delay blasting, are formed in the case of the millisecond delay blasting. The arrangements of boreholes used in these experiments are shown in Fig. 2. All the boreholes were drilled in parallel and perpendicular to the free face and their depths were about 1.0 meter. The strain gauges were placed at each bottom of the three holes located at the center. Throughout these experiments Shinkiri dynamite was charged in the right and left holes and the amount of the charges per each hole was 200 grammes for every shot. The distance between the shot points and the strain gauges under above conditions were from 1.0 meter to 1.25 meters. Two examples of the oscillograms showing the types of the strain waves obtained are shown in Figs. 3 (a) and 3 (b). The type shown in Fig. 3 (a) was obtained in the case of blasting with the delay interval of 2 milliseconds and the

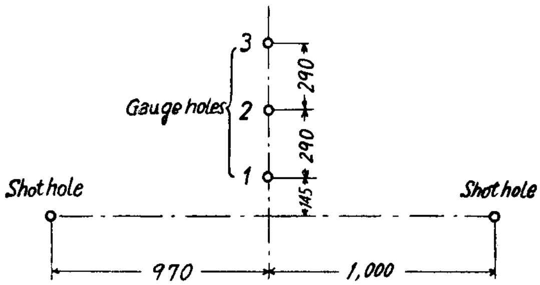

Fig. 2. Arrangement of boreholes in the millisecond delay blasting.

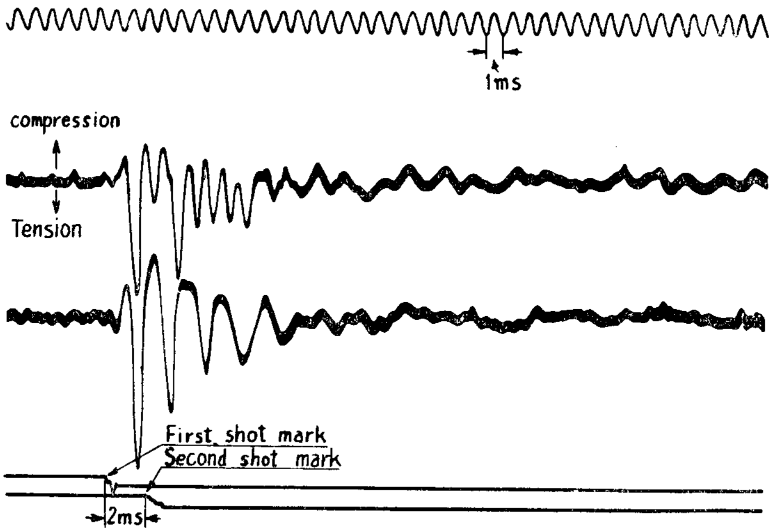

Fig. 3 (a). An oscillogram obtained in delay blasting with delay time of 2 ms.

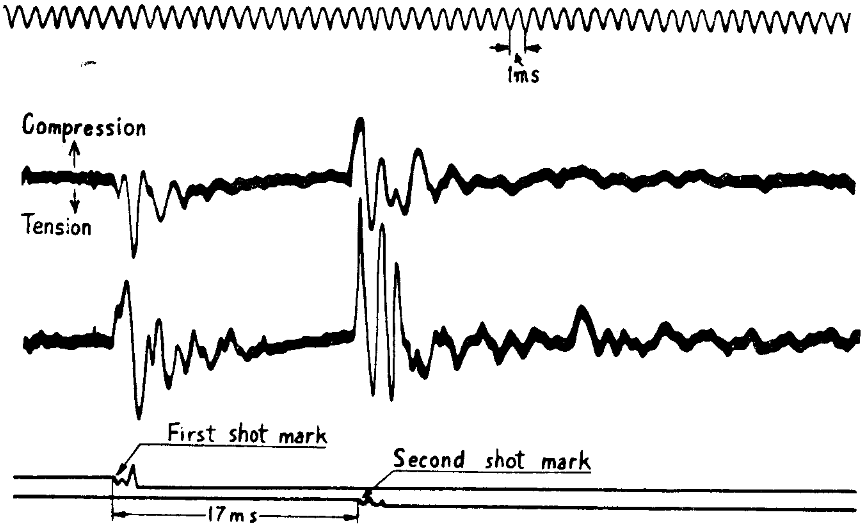

Fig. 3 (b). An oscillogram obtained in delay blasting with delay time of 17 ms.

other shown in Fig. 3 (b) was obtained in the case of blasting with the delay interval of 17 milliseconds.

The characteristics of the strain waves obtained in these experiments are shown in Table 3 and these characteristics can be summarized as follows. The waves which had the frequencies in the neighbourhood of 1,000 cps were predominant and the velocity of propagation of the strain wave was 2,910 m/sec on the average. These characteristics are considered peculiar to the hedenbergite of the Kamioka mine and, they were almost identical in both cases of the single shot-firing and the millisecond delay blasting. The durations of the strain waves appeared in the present records were comparatively long as compared with those for the single shot-firings, and they were in the range of from 8 milliseconds to 25 milliseconds depending on the conditions of the shot points. For the superposition of the strain waves on which we were mostly concerned, the following could be concluded. In the present experiments in which the distance between the shot point and the strain gauge was about 1.0 meter or a little more, and the delay interval between two shots was shorter than 5 milliseconds, it was observed that the strain induced by the second shot superposed over that induced by the first shot and it was difficult to distinguish each strain separately. Even in these cases the total duration of the strains was not so long as compared with the individual strains; in other words, the tendency to prolong the duration of strain due to its superposition could not be observed. On the other hand when the delay interval between the two shots was longer than 5 milliseconds, each strain was

Table 3. Radial strain in hedenbergite in the case of millisecond delay blasting.

No. of gauge	Strain due to	Delay interval (ms)	Distance from shot point (m)	Frequency of strain wave (cps)			Velocity of propagation of strain wave (m/sec)	Duration of strain wave (ms)	Magnitude of radial strain ($\times 10^{-5}$)
				Maximum	Minimum	Mean			
1	1st and	0	1.04	1,230	—	1,230	2,480	8.7	25.4
2	2nd shots		1.28	680	400	580	2,730	8.8	25.7
1	1st and	1.9	1.01	960	610	830	2,150	23.3	32.8
2	2nd shots		1.10	910	380	750	2,100	21.1	19.6
1	1st and	2.2	1.00	3,890	630	1,550	3,530	11.0	10.0
2	2nd shots		1.08	1,340	610	1,000	2,540	8.4	6.2
1	1st and	4.7	1.00	860	730	790	2,160	17.2	10.2
2	2nd shots		1.04	2,030	600	1,110	2,110	22.7	4.7
1	1st shot	13.4	1.02	1,380	610	890	2,900	7.8	15.3
1	2nd shot		1.02	1,080	690	900	2,900	9.1	9.4
1	1st shot	17.4	0.86	1,100	510	780	4,400	13.5	30.6
2			1.13	1,330	510	890	3,900	13.5	13.6
1	2nd shot		0.86	1,100	610	750	2,500	24.9	27.7
2			1.13	1,100	830	920	2,170	24.9	9.9
1	1st shot	41.0	1.03	1,670	530	1,040	3,930	10.5	12.9
2			1.25	1,180	420	850	3,120	12.0	20.8
1	2nd shot		1.03	1,110	830	990	3,930	21.0	23.1
2			1.25	1,000	690	920	3,120	14.0	19.2

recorded separately and the superposition of the strain could not be recognized. In these cases the duration of the strain due to the second shot was somewhat longer than that caused by the first shot.

Concerning the magnitude of the strain in the case of the delay blasting, there was no conspicuous differences in the magnitudes of the strain caused by the first and second shots, and even in the cases where the strain due to the second shot superposed over the residual strain due to the first shot, no definite increase of the strain due to the superposition could be observed. It is felt that this fact is important for consideration of the mechanism of the millisecond delay blasting.

Here we shall quote for reference a part of our theoretical calculations for the strain induced in rocks in the case of blasting by utilizing the expression introduced by W. I. Duvall.[2)]

In these calculations, we assumed the detonation pressure of the following two types as the function of time.

$$P_t = P_0 N\left(e^{-\frac{\omega t}{\sqrt{2}}} - e^{-\sqrt{2}\,\omega t}\right) \tag{2.1}$$

$$P_t = P_0 N\left(e^{-\frac{\omega t}{100\sqrt{2}}} - e^{-\frac{\omega t}{\sqrt{2}}}\right) \tag{2.2}$$

As shown in Fig. 4, the pressure represented in Equation (2.1) is a type in which both the pressure increase and decrease are rapid, consequently the pressure drops very rapidly after the explosives are detonated, on the other hand, the pressure represented in Equation (2.2) is a type in which it increases rapidly but decreases gradually, consequently the pressure acts fairly long time after the explosives are detonated.

The variation of the radial strain at a point, ten times of the radius of a spherical charge measured from the center of the explosion, is shown in Fig. 5.

As shown in this figure, the radial strain at a point apart from the center of explosion begins with an oscillatory form within the first short period and the maximum strain occurs soon after explosion. After this stage the strain decreases gradually taking a non-oscillatory form. These characteristics of the strain seem to be common regardless of the form of the detonation pressure and, even where the detonation pressure acts fairly long time as in the case shown in Equation (2.2), the duration of the comparatively large strain is extremely short.

The above results obtained

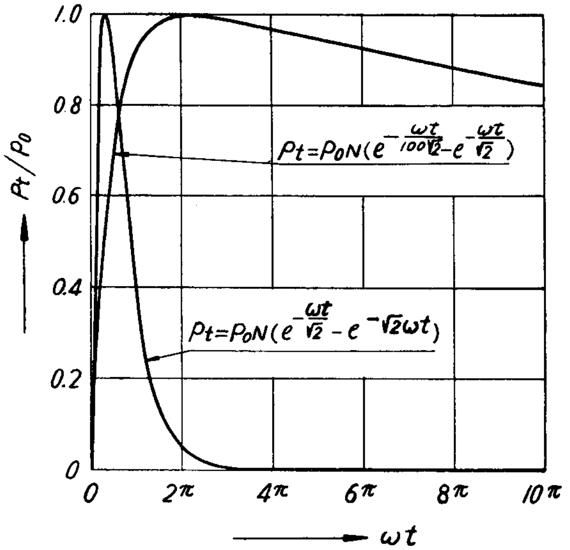

Fig. 4. Variation of pressure Pt against ωt.

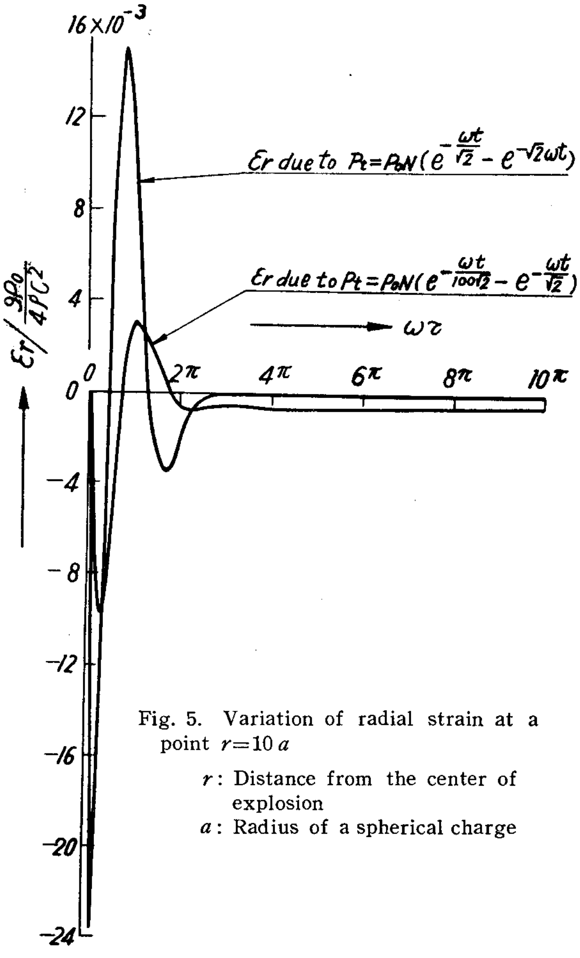

Fig. 5. Variation of radial strain at a point $r=10a$

r: Distance from the center of explosion

a: Radius of a spherical charge

theoretically seem to be very important in considering the duration of the strain in rocks. The strain decays very rapidly after explosion: therefore, where delay blasting with fairly long interval is carried out, the strains due to each shot are induced separately and in this case the strains do not superpose each other. This fact coincides well with our experimental results already described above.

3. The period of the Rock Burst

To measure the moment of the rock burst after explosion, commercial neon glow tubes (25 mm$\phi \times$60 mm) or a kind of special electric contacts were used. When a neon glow tube in the discharging state is broken mechanically with the rock in which it is placed, its circuit will be opened, thereby the moment of the rock burst can be obtained by measuring on the electromagnetic oscillograph the moment at which the discharging circuit containing the neon glow tube is opened. The construction of the special electric contact is shown in Fig. 6. It is so designed as to close the electric circuit when the metal case installed in the rocks touches a center piece the moment a displacement of about one millimeter occurs in the rocks. The measurement with this instrument, therefore, is based upon an assumption that the rock is crushed when a displacement of about one millimeter occurs in itself. These measurements were carried out similarly by using the electromagnetic oscillograph. The natural frequency of this system including a center piece is designed to be 30 cps.

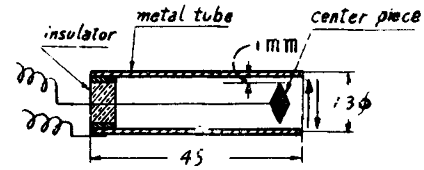

Fig. 6. Special electric contact.

An example of arrangement of boreholes for this kind of experiments is shown in Fig. 7. A neon glow tube or a special electric contact is inserted at each bottom of the five boreholes respectively and it is settled with tamping clay materials. In the case of an experiment with the arrangement of boreholes shown in this figure, the length of the line of least resistance was 62 centimeters and the amount of charge exploded was 800 grammes of Murasaki Carlit. The hatched portion in the figure represents the range of the crush.

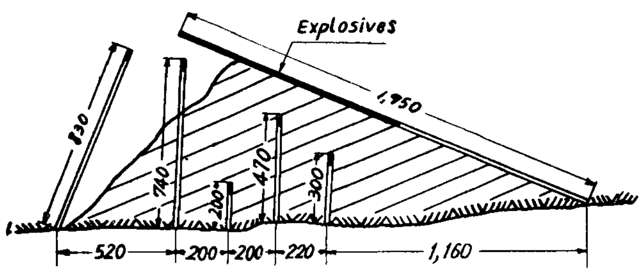

Fig. 7. An example of arrangement of boreholes.

The measured time obtained in these experiments are shown In Fig. 8 against the distance from the charge.

Although the measured time scatters in a fairly wide range as shown in the figure, it can be said from these results that the breaking of the rock due to explosion at a point in the rock mass occurs immediately after the shock wave passes this point or a little later than that.

Besides the above experiments, a brittle wire was stretched along the free face of the rock and the time at which this wire was cut off by the flying broken rock was measured electrically. As the results of these experiments, it was found that the measured time was from 4.5 milliseconds to 5.3 milliseconds when the length of the line of least resistance was 90 centimeters and the time decreased to 3.7 milliseconds when the length of the line of least resistance decreased to 50 centimeters. From these facts it can be said that the rushing out of the broken rocks at the free face occurs at least a few milliseconds after explosion.

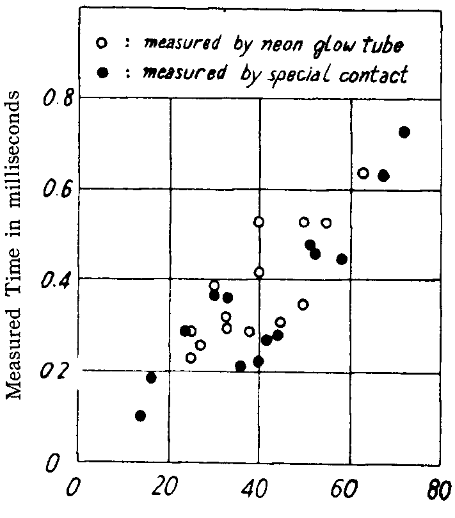

Fig. 8. Period of rock burst at various points.

4. Breaking of the Rock under Compression by the Explosion Attack

In the process of blasting there is a stage in which the rocks around the explosion are under a great compression due to the expansion of gases. It is interesting to know to what extent the rocks under such a condition will be crushed when they are attacked by another shock of explosion. The following simple experiments were conducted to examine the above phenomenon.

Specimens of about 5 centimeters cube and 7 centimeters cube were selected and two steel plates were attached to the upper and lower sides of the specimen. The specimen was pressed through these steel plates until it suffered under a proper load and all its lateral sides were kept free. An electric detonator was set in a hole of about 3 millimeters in depth which was bored at the center of a lateral side of the specimen. Then the detonator was fired and the rock was broken. The experiment was performed in a large wooden box. After the explosion, the rock fragments were gathered and the sizing analysis was made to examine the fragmentation.

As the specimens the coarse grained limestones from Yamaguchi prefecture were selected, and for the specimen 5.1×5.1×4.1-cm in size a No. 6 electric detonator was used and for the specimen 7.0×7.0×7.0-cm in size a No. 3 electric detonator was used. The results of the experiments are shown in Table 4.

Table 4. Results of experiments on the breaking of rocks under compresssion by explosion attack.

(a) Experiment 1
Specimen: Limestone, 5.1×5.1×4.1-cm.

Load imposed (tons)		1.0			2.62		
Stress in specimen (kg/cm²)		48.7			127.1	130.8	
Detonator used		No. 6 Electric detonator					
Number of experiment		1	2	mean	1	2	mean
Results of sizing analysis (weight percentage)	+ 8 mesh	56.2	34.4	45.3	19.7	15.9	17.8
	−8 + 10 〃	7.6	10.1	8.9	12.0	6.7	9.3
	−10 + 20 〃	21.8	32.7	27.3	35.1	31.0	33.1
	−20 + 65 〃	13.2	20.2	16.7	25.7	38.8	32.3
	− 65 〃	1.2	2.6	1.9	7.6	7.7	7.6
	Total	100.0	100.0	100.1	100.1	100.1	100.1

(b) Experiment 2
Specimen: Limestone, 7.0×7.0×7.0-cm.

Load imposed (tons)		0.5	1.0				2.0				3.0		
Stress in specimen (kg/cm²)		10.2	20.4				40.8				61.2		
Detonator used		No. 3 Electric detonator											
Number of experiment		1	1	2	3	mean	1	2	3	mean	1	2	mean
Results of sizing analysis (weight percentage)	unbroken mass	98.6	89.8	92.7	99.1	93.9	86.5	81.5	97.7	88.6	87.3	88.5	87.9
	+ 3 mesh	0.3	7.3	5.7	0.0	4.3	9.8	10.4	0.5	6.9	10.7	8.5	9.6
	−3 + 10 〃	0.6	1.6	1.0	0.5	1.0	2.1	4.9	1.0	2.7	1.2	1.6	1.4
	−10 + 35 〃	0.4	0.9	0.5	0.3	0.6	1.0	2.5	0.7	1.4	0.6	1.1	0.8
	−35 + 65 〃	0.1	0.2	0.1	0.0	0.1	0.2	0.3	0.1	0.2	0.1	0.2	0.2
	− 65 〃	0.1	0.2	0.1	0.0	0.1	0.2	0.3	0.2	0.2	0.2	0.2	0.2
	Total	100.1	100.0	100.1	99.9	100.0	99.8	99.9	100.2	100.0	100.1	100.1	100.1
Breaking load of the unbroken mass by another compression test (tons)		19.76	13.93	15.46	17.49	15.63	16.98	10.90	9.88	12.59	14.19	10.13	12.16

On account of the imperfect arrangements in these experiments, it is conceivable that a secondary fragmentation due to collision against the surrounding boards of the box or to collision of fragments against each other is included in the above results, however, in Experiment No. 1 where the size of the rock specimen was $5.1 \times 5.1 \times 4.1$ cm and a No. 6 electric detonator was used it was clear that the specimens were crushed more finely as the load upon them increased. But in the case of Experiment No. 2 where the size of the rock specimen was somewhat larger than the former one and a weaker electric detonator was used, a large mass of the specimen remained unbroken while the broken fragments of the specimen generally showed the above tendency. Then these unbroken masses were crushed by ordinary compression test. The results of these compression test showed, as shown in the lowest line of Table 4 (b), that the unbroken masses which were suffered under a great load previously were crushed with weaker compression, in other words, that they were in the state of more easily broken.

Consequently, it is shown, within the scope of this experiment, that, when the rock under compression is attacked with a proper strength of shock, it is crushed more finely as the load, which has been previously imposed upon it, increases.

However, more detailed experiments must be made to examine the above phenomenon.

5. The Mechanism of the Millisecond Delay Blasting

Generally the breakings of the rock by explosion of the explosives are performed in two stages. The first stage of breakings is the one that is performed by the shock effects caused by explosion, and the second stage is the one that is performed by the expansion of gases produced by the chemical reactions between the explosive constituents. In the first stage the shock wave plays a leading role and therefore the breaking in this stage is clearly a dynamical one. Cracks and fissures are produced in rocks by this shock effect and the rocks are broken into large slabs or masses, but they do not commence to fly out of the place in this stage. On the other hand in the second stage, the gases produced tend to expand and exert a great pressure against the surrounding rocks and therefore the breaking in this stage is considered a static one. In this stage large slabs or masses of rocks preduced in the first stage are crushed more finely and the fragments of rocks rush out towards the free face as one body.

Now, how long these actions of breaking last in the rocks, we feel, is quite important. According to our experiments described in the preceding paragraph, the breaking of the rocks occurs immediately after the shock wave passes or a little later than that. This breaking corresponds to the one associated by the shock wave, so it belongs to the breaking in the first stage. Although the shock wave produced by explosion decays very rapidly and soon it turns to the elastic wave, the velocities of propagation of these waves in rocks are generally about a few thousand meters per second so, even if we consider the reflections of these waves at various boundary faces, the total time in which these waves affect on the breaking of rocks will be instantaneous and it is estimated to be approximately 1~2 milliseconds after explosion at the maximum.

Moreover from our measurements of the strain in rocks, it has been clarified that the greater part of the strains induced in rocks due to explosion decays very rapidly within a few milliseconds after explosion and, in the case of the delay blasting, the superposition of the strains due to the first and second shots can not be realized when the delay interval is over 5~6 milliseconds. From these facts, an opinion that the breaking action in the first stage plays an important part in promoting its effects in the case of the millisecond delay blasting seems to be unreasonable. Therefore, we must rather pay our attention to the breaking action in the second stage.

Now, as mentioned previously, the rushing out of the rock fragments at the free face occurs a few milliseconds after explosion. In addition, the results of our experiments[3)] made at the Ikuno mine revealed the fact that the rushing out of the rock fragments begins from the free face and it develops towards the interior with the speed of 100~150 m/sec. Judging from these facts, when the length of the line of least resistance is one meter or so, it seems to take at least about 20 milliseconds to produce a complete crater. The range of this interval is likely to vary depending not only upon the properties of the rocks but also upon the conditions of blasting such as the kind of explosives used, the length of the line of least resistance, the arrangement of the boreholes, the quality of the tamping materials and so on.

In this way, since the breaking action in the second stage lasts fairly long time and, in the case of millisecond delay blasting, the second shot is detonated while the breaking action of the second stage caused by the first shot is in progress; both the breaking actions caused by the shock wave and by the successive expansion of gases due to this second shot promote the fragmentation. The phenomenon that the shock wave promotes the fragmentation of the rock under pressure is also supported by our simple experiments already described in the previous paragraph.

The above explanation on the mechanism of the millisecond delay blasting which has been concluded from our researches seems to be most reasonable and it is in agreement with the opinion proposed by Dr. Hino.

In conclusion, it seems that the peculiar features of the existing delay blastings with the delay intervals ranging from 20 milliseconds to 50 milliseconds lie in promoting the secondary fragmentations and the increase of the shock effects can scarcely be expected in them.

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