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Concussion Mortar Internal Pressure, Recoil and Air Blast as Functions of Powder Mass

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ABSTRACT

A concussion mortar is a device used to produce jarring explosive sounds at events such as concerts and other theatrical productions. It consists of a heavy steel bar, drilled out to produce an explosion chamber. A type of pyrotechnic flash powder is loaded into the explosion chamber and fired with an electric match. Although concussion mortars are used quite frequently, for the most part, detailed measurements of their manner of functioning have not been reported in the literature. In the present study of concussion mortars, internal mortar pressure, recoil force and air blast were measured as functions of concussion powder load. It was determined that a full load (1 oz. or 28 g) of a strontium nitrate and magnesium concussion powder produced peak internal pressures averaging approximately 3100 psi (21 MPa). It was also observed that the width of the pressure peak ranged from approximately 7 ms for light loads, down to less than 2 ms for heavy loads. The recoil produced for a full load averaged approximately 5.9 lbf·s (26 N·s). The air blast for a full load, at a point 5 feet from and 3 feet above the mortar (1.52 m and 0.91 m, respectively), averaged approximately 1.5 psi (10 kPa). In addition, there were a number of unexpected observations, some of which have not been fully explained at the time of this writing.

Introduction

The present study is an extension of an earlier work by one of the authors,[1] and was undertaken to more completely characterize and understand the functioning of concussion mortars. (Concussion mortars are used to produce jarring explosive sounds at events such as concerts and other theatrical productions.) It was felt that a more thorough study of concussion mortars was appropriate for two reasons. The first reason is that, because of the likelihood of persons being located relatively near concussion mortars when they are fired, safety may be better assured through a more complete understanding of their operating characteristics. The second reason is simply that the study was expected to yield intrinsically interesting results that have not been reported elsewhere in the literature.

Typically, a concussion mortar consists of a massive steel bar approximately 2 inches (50 mm) in diameter, which has been welded to a heavy steel base plate. The steel bar contains an explosion chamber, produced by drilling an approximately 1-inch (25-cm) diameter hole—on axis—into one end of the bar, to a depth of 4 to 5 inches (100 to 120 mm). The construction of a concussion mortar is illustrated in Figure 1, which also demonstrates its loading with a charge of concussion flash powder and one method of installing an electric match. Upon firing the electric match, and because of the partial confinement, the concussion powder burns explosively (see Figure 2). The high pressure created in the

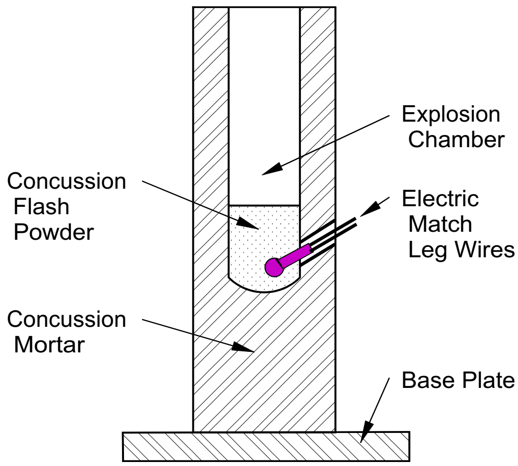

Figure 1. An illustration of the construction and setup of a concussion mortar.

explosion chamber results in the combustion gases being forced rapidly upward and out of the concussion mortar's explosion chamber. This necessarily produces a downward reactive force, the recoil of the mortar. As the high velocity gases exit the mortar, they expand as a shock wave, producing the air blast that is heard and felt by the audience. With a concussion flash powder that is fuel rich, such as the one used in this study, there will be additional burning of the exiting gases as they mix with oxygen from the air.

In this study, internal mortar pressure, recoil force, and air blast pressure—as functions of concussion powder load—were investigated. Internal mortar pressure is of interest to assure that in designing concussion mortars there is an adequate safety margin in the strength of its explosion chamber. Mortar recoil force is of interest to assure that the placement of concussion mortars can be such that their recoil will not damage other equipment. Air blast pressure is of interest to assure that the placement of concussion mortars is such that the hearing of persons will not be impaired as a result of its use. (Note that the present study only provides limited air blast data, and that additional studies are anticipated by the authors.)

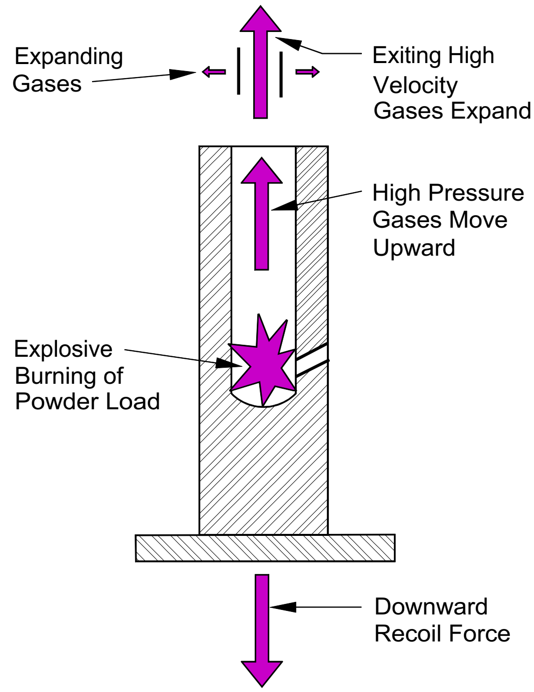

Figure 2. An illustration of the firing of a concussion mortar.

Experimental Method

A concussion mortar was modified as illustrated in Figure 3. A hole was drilled into the bottom of the explosion chamber, which, after threading, allowed the mounting of a pressure transducer to measure the high internal pressures produced upon firing the mortar. In addition, a hinge assembly was attached to one end of the base plate of the mortar, and the mortar was positioned such that the bore of the explosion chamber was located directly over a force transducer. The pressure transducer was a quartz piezoelectric gauge with a 0 to 75,000 psi (0 to 520 MPa) range, manufactured by Kistler Instrument Corp. (model 617C). The Kistler gauge produces a current output pulse, which was converted to a voltage pulse using a PCB Piezotronics voltage amplifier (model 401A03). The force transducer was also a quartz gauge, with a 0 to 5000 lbf (0 to 22 kN) range, manufactured by PCB Piezotronics (model 208A05).

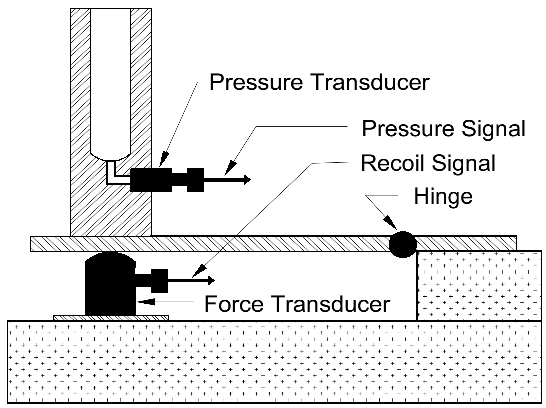

Figure 3. An illustration of the modified concussion mortar used to collect internal mortar pressure and recoil force data.

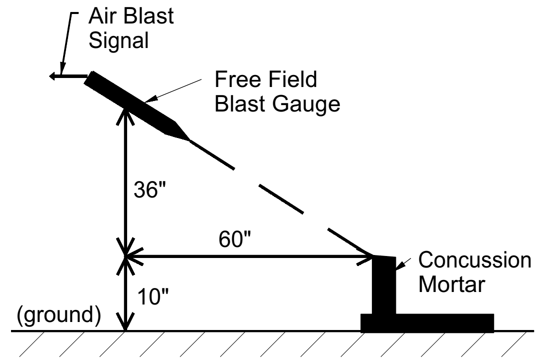

Figure 4. An illustration of the physical setup used to collect concussion mortar air blast data.

Air blast measurements were taken with the equipment setup as illustrated in Figure 4. The data was generated using a free-field blast probe aimed at the muzzle of the concussion mortar from a point 5 feet (1.52 m) distant and 3 feet (0.91 m) above. The pressure transducer has a ceramic sensing element with a blast pressure range of 0 to 50 psi (0 to 340 kPa) and was manufactured by PCB Piezotronics (model 137A12). This particular type of pressure transducer is somewhat temperature sensitive. Because the concussion powder used was quite metal fuel rich (see below), upon firing, a significant thermal pulse was generated. To eliminate the effect of the thermal pulse on the pressure measurements, the pressure transducer was covered with a thin film of silicon grease; then a 0.001 inch (0.025 mm) thick film of aluminized mylar was used to tightly cover the grease. While it is possible these measures had an effect on the pressure data recorded, it is felt any effect was small enough to be ignored in this study.

In each case, the power source for the gauges was an amplifying battery power unit manufactured by PCB Piezotronics (model 480D09). The results were recorded and temporarily stored using a digital oscilloscope and a digital storage unit. Permanent storage and plotting of the data was accomplished through the use of a personal computer.

The pyrotechnic powder used in the measurements was Luna Tech's Pyropak Concussion Flash Powder, supplied as a two-component (binary) system in packaging of 1.0-ounce (28 g) units. This is a fuel rich (approximately 1.5 times the stoichiometric amount of magnesium) combination of strontium nitrate and magnesium. The mixed powder was weighed and loaded loosely into the top of the concussion mortar. The powder was ignited using a Pyropak "BN" type electric match, which was inserted through a small hole near the bottom of the explosion chamber of the mortar (shown slightly enlarged in Figure 1). An attempt was made to be consistent in the placement of the electric match; this was accomplished each time by inserting the match as far as possible and then withdrawing it about 1/8 inch (0.3 cm) to raise it slightly off the bottom of the explosion chamber.

Between each mortar firing, the bore of the mortar (explosion chamber) was cleaned and to some extent cooled. This was accomplished using compressed air and a large test-tube brush. In part this was done for consistency in the results; however, it was also done for safety. Large numbers of measurements were being made, often with only a few minutes between mortar firings. In more than one case, even several minutes after a firing, live (incandescent) sparks were blown from the mortar upon cleaning. It was feared that there could possibly have been a premature ignition of the concussion powder while loading, had the mortar not been well cleaned between firings.

Concussion Mortar Internal Pressure

Substantially different internal pressure profiles (pressure versus time) were obtained for light and heavy concussion flash powder loads. Figure 5 presents somewhat typical pressure profiles for light (<12 g) and heavy (>12 g) powder loads. It was common for light loads to exhibit broad and undulating pressure peaks, while heavy loads essentially always produced fairly narrow single peaks. There was also considerable variation between pressure profiles from shot to shot even for the same powder load. This was especially true for intermediate concussion powder loads (8 to 14 g) when either broad undulating or single peaks occurred intermittently; see Figure 6. The full set of internal mortar pressure data is presented in Table 1.

Table 1. Internal Concussion Mortar Pressure Data

Load (g)	Peak Pressure (psi)	FWHM (ms)	Impulse (psi·s)
2	41	6.7	0.22
2	46	6.3	0.22
3	95	5.9	0.48
4	131	8.3	0.63
5	163	7.2	0.91
6	189	5.2	1.16
7	211	7.8	1.32
7	184	7.3	1.31
8	268	5.7	1.70
8	226	6.6	1.44
9	194	11.4	1.70
9	295	6.2	1.91
10	395	5.2	2.08
11	353	6.2	2.19
11	874	2.4	2.42
12	1050	2.0	2.72
12.5	647	4.1	2.82
13	1190	2.3	3.07
13	1540	1.6	2.93

Table 1. Internal Concussion Mortar Pressure Data (continued).

Load (g)	Peak Pressure (psi)	FWHM (ms)	Impulse (psi·s)
14	1450	1.8	3.12
14	1580	1.7	3.01
14	1470	1.8	3.13
14	1710	1.6	3.03
14	1290	2.2	3.14
14	1180	2.1	2.72
14	1890	1.4	3.14
14	1630	1.5	2.55
14	1660	1.4	2.59
16	2210	1.3	2.32
17	2260	1.6	3.70
18	1890	1.6	3.12
19	2470	1.5	3.57
20	2390	1.8	4.02
21	2050	1.8	3.92
21	1820	1.8	3.30
21	2050	2.0	4.27
21	2790	1.4	3.79
21	1970	2.0	4.18
21	2710	1.9	5.28
21	1970	1.3	2.68
22	1870	1.6	2.97
23	2580	1.6	4.43
24	2890	1.7	4.14
25	2500	1.5	3.77
26	2870	1.8	4.65
27	2890	1.9	5.23
28	2870	2.1	5.74
28	2710	1.9	4.86
28	3160	2.1	6.13
28	3680	2.1	5.05
28	3420	1.8	6.06
28	2710	1.8	4.88
28	3470	1.8	6.12
28	2710	1.9	5.34
28	2930	1.8	5.43

(For conversion to SI units, 1 psi = 6.89 kPa.)

FWHM = Full-width at half maximum.

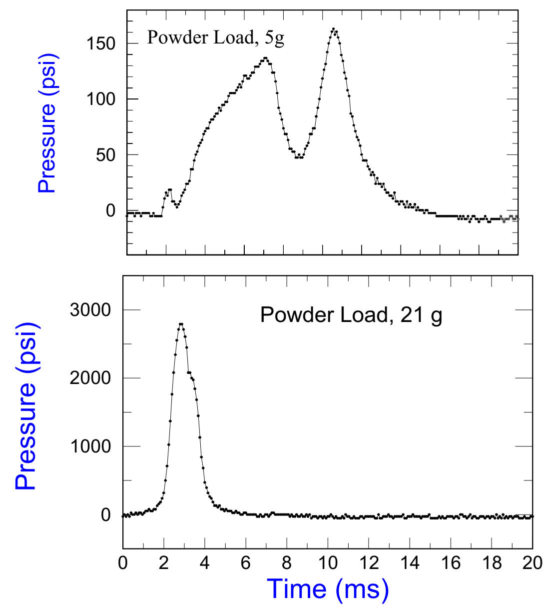

Figure 5. A comparison of typical concussion mortar internal pressure profiles for light and heavy powder load masses. (For conversion to SI units, 1 psi = 6.89 kPa.)

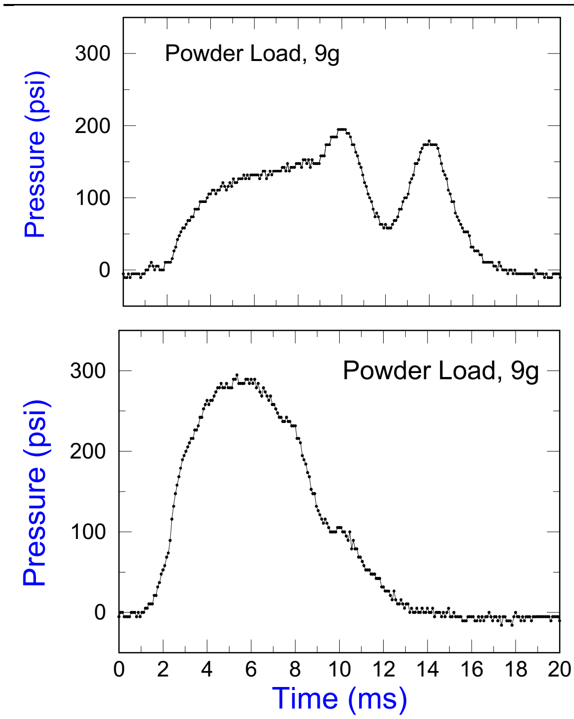

Figure 6. A comparison of two internal, pressure profiles for the same medium concussion powder load mass. (For conversion to SI units, 1 psi = 6.89 kPa.)

Peak width information, expressed as the full-width-at-half-maximum (FWHM), for the pressure peaks, is also included in Table 1. This method was chosen as the indicator of peak width, because of the ease of determination and the subjectiveness of otherwise establishing precisely where these peaks begin and end. Figure 7 is a graph of FWHM for pressure peaks as a function of concussion powder load mass. Note the transition from relatively broad to narrow pressure peaks that occurs around 11 g loads.

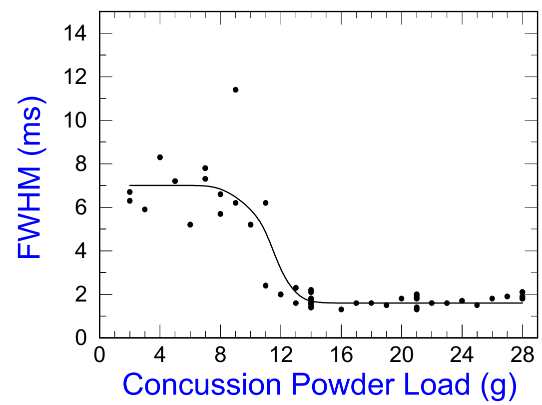

Figure 7. A graph of full-width-at-half-maximum (FWHM) for internal pressure peaks as a function of concussion powder load mass.

Peak internal mortar pressure as a function of powder load is presented as a graph in Figure 8. Because of the varying width of the peaks seen in the pressure profiles with increasing powder load, time integrated data (pressure impulse) was generated as a better estimator of the total energy released per mortar firing, see Figure 9.

In one brief set of measurements, internal mortar pressures were taken with a second pressure transducer installed in the side of the mortar, 1.5 inches (3.8 cm) below the muzzle. In these tests, because the high velocity gases were moving parallel to the bore of the mortar, significantly reduced pressures were recorded for the upper location. These results are presented in Table 2.

Table 2. Comparative Internal Pressure Data.

Load (g)	Peak Pressure Bottom (psi)	Peak Pressure Top/Side (psi)	Pressure Ratio
14	1710	950	0.56
14	1290	720	0.56
14	1180	820	0.69

(For conversion to SI units, 1 psi = 6.89 kPa.)

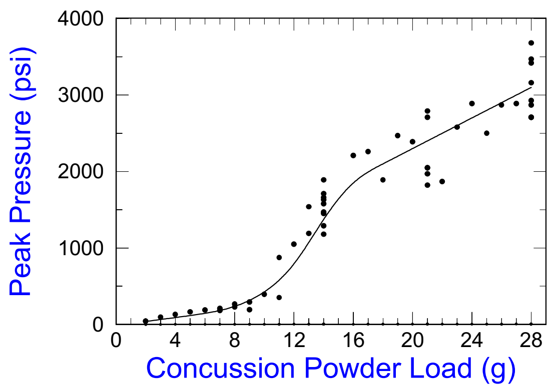

Figure 8. A graph of peak internal pressure as a function of concussion powder load mass (For conversion to SI units, 1 psi = 6.89 kPa).

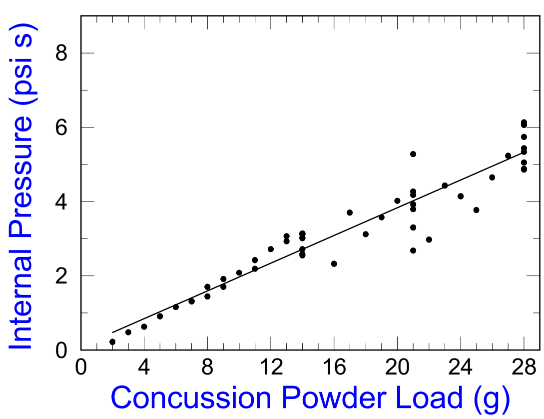

Figure 9. A graph of time integrated internal pressure (Pressure Impulse) as a function of concussion powder load mass. (For conversion to SI units, 1 psi·s = 6.89 kPa s.)

Concussion Mortar Recoil

For concussion mortar firings, the recoil force profile has the same approximate shape as the internal pressure profile; for an example, see Figure 10. The similarity of the two profiles is fairly obvious, particularly if the last doublet peak is mentally smoothed into a lower resolution singlet. However, there is a systematic shift in the timing of the peaks, with the recoil force peaks falling progressively farther behind the internal pressure peaks. In Figure 10 note that the first peaks (labeled as "1") occur at essentially the same time; there is nearly a 1 ms shift between the second peaks ("2"); and there is approximately a 2 ms shift in the timing of the third peaks ("3"). Similar time shifting of the peaks occurred whenever there were clearly defined multiple peaks. Somewhat similarly, when only single peaks were produced, every time the pressure peak always preceded the recoil peak by about 0.5 ms.

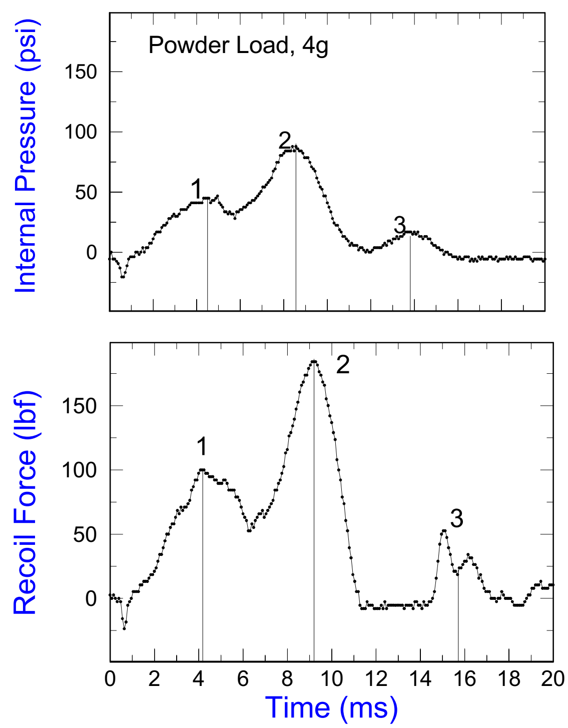

Figure 10. A comparison of an internal pressure profile and the recoil force profile for the same concussion mortar firing.
(For conversion to SI Units, 1 psi = 6.89 kPa, and 1 lbf = 4.45 N.)

The full set of recoil force measurements is presented in Table 3. The width of recoil force profiles varied much like they did for internal pressure. However, there was an additional factor that affected the widths of the recoil force peaks; that is, the nature of the surface upon which the concussion mortar was placed. When the surface is very firm and hard, such as a concrete slab, the recoil force peaks are relatively narrow. When the mortar is placed on a more yielding surface, such as the ground or on thick carpet, wider peaks are produced. For example, consider the recoil force data reported in Table 3 for full powder loads (1.0 ounce, 28 g). The first four measurements (28-a) were made with the concussion mortar placed firmly on a concrete slab, the next five measurements (28-b) were made with the mortar on the ground, and the last three measurements (28-c) were made with the mortar placed on thick carpet. A summary of these results is given in Table 4. Note that there is a substantial increase in average peak width (46% and 410% when on the ground and carpet, respectively), accompanied by a significant decrease in peak force (27% and 66%, respectively). Note however, that the time integrated recoil force is much less affected (5% and 22% reductions, respectively). During the course of taking the recoil force data in this study, because of operational constraints, the location of the equipment was changed several times. Accordingly, it is felt that only the time integrated -

Table 3. Concussion Mortar Recoil Force Data.

Load (g)	Force (lbf)	FWHM (ms)	Impulse (lbf s)
2	52	7.7	0.27
2	56	6.9	0.26
3	91	6.3	0.46
4	131	6.0	0.61
5	150	8.6	0.90
6	175	4.4	1.10
7	211	7.4	1.26
8	269	6.9	1.48
8	277	5.2	1.50
9	213	12.5	1.58
9	303	6.0	1.69
10	366	5.7	1.92

Table 3. Concussion Mortar Recoil Force Data. (Continued)

Load (g)	Force (lbf)	FWHM (ms)	Impulse (lbf s)
11	299	6.7	2.06
12	1090	2.2	2.48
12.5	538	4.1	2.39
13	1400	1.8	2.68
14	1980	1.4	3.07
14	2110	1.3	3.10
14	1940	1.4	3.04
14	1910	1.4	3.01
14	1910	1.4	3.05
16	2540	1.3	3.68
17	2840	1.3	3.96
18	2370	1.4	3.44
19	3010	1.4	4.32
20	3210	1.3	4.44
21	2970	1.3	4.03
21	2490	1.3	3.44
21	2920	1.4	4.19
21	3100	1.6	4.93
21	3070	1.6	4.88
21	2470	1.7	4.52
21	3140	1.6	5.23
21	2360	1.6	3.92
22	3850	1.1	4.76
23	4190	1.2	5.27
24	4410	1.1	5.15
25	3960	1.2	5.02
26	4600	1.1	5.65
27	4710	1.1	5.65
28-a	4640	1.2	5.92
28-a	4450	1.2	5.66
28-a	5050	1.1	6.22
28-a	5500	1.1	6.50
28-b	4110	1.6	6.43
28-b	3140	1.8	5.23
28-b	4070	1.6	6.46
28-b	2950	1.8	5.06
28-b	3550	1.6	5.62
28-c	1380	6.3	4.49
28-c	2170	5.0	5.28
28-c	1350	6.2	4.43

(For conversion to SI units, 1 lbf = 4.45 N.)

Notes: a- Mortar on concrete.
b- Mortar on ground.
c- Mortar on carpet.

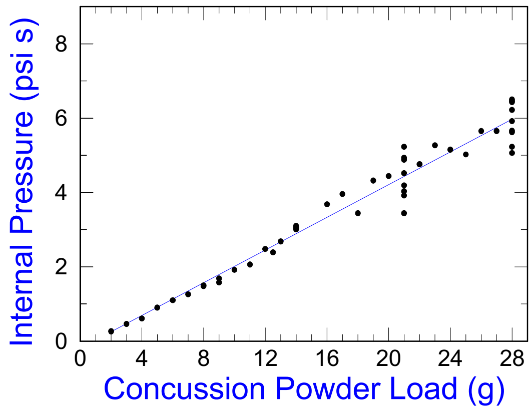

Figure 11. A graph of time integrated mortar recoil force (Impulse) as a function of concussion powder load mass. (For conversion to SI units, 1 lbf = 4.45 N.)

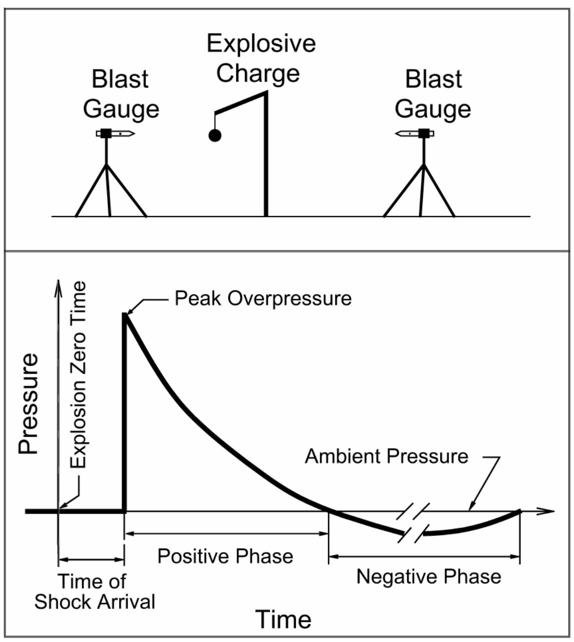

Figure 12. An illustration of a typical setup and blast profile from an explosive charge.

recoil force data (impulse) rather than the peak force results is sufficiently consistent to be relied upon. Recoil impulse data is presented in Figure 11.

Table 4. Average Results of Changing the Support Surface for the Concussion Mortar Fired with 28 g (1.0 ounce) Loads.

Parameter Averages	Concrete	Ground	Carpet
Peak Pressure (psi)	4910	3560	1630
FWHM (ms)	1.15	1.68	4.73
Impulse (psi·s)	6.08	5.76	4.73

(For conversion to SI Units, 1 psi = 6.89 kPa.)

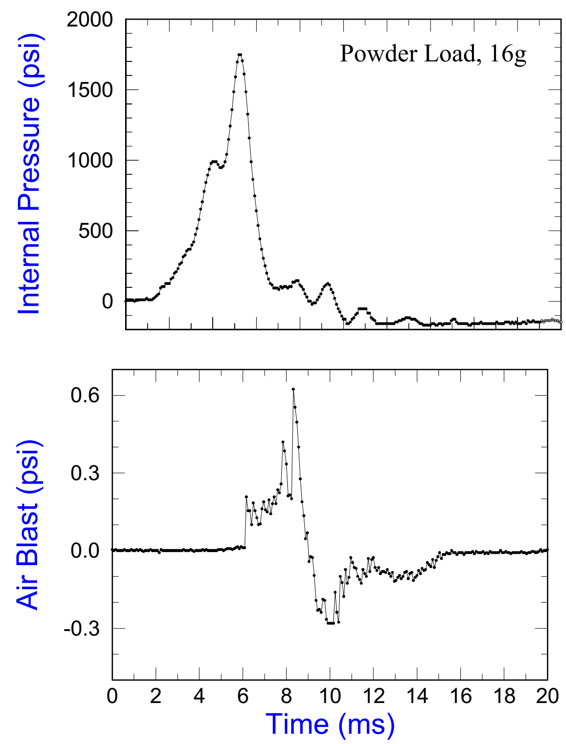

Figure 13. A comparison between an internal mortar pressure profile and an air blast profile for the same mortar firing. (For conversion to SI Units, 1 psi = 6.89 kPa.)

Concussion Mortar Air Blast

The air blast profiles (blast pressure versus time) do not have the same appearance as those from the explosion of individual charges such as illustrated in Figure 12. During the course of taking data, a few firings were accomplished in which internal mortar pressure and air blast data were recorded simultaneously. A comparison of the results suggests that when taken near the concussion mortar, approximately 5.8 feet (1.8 m),

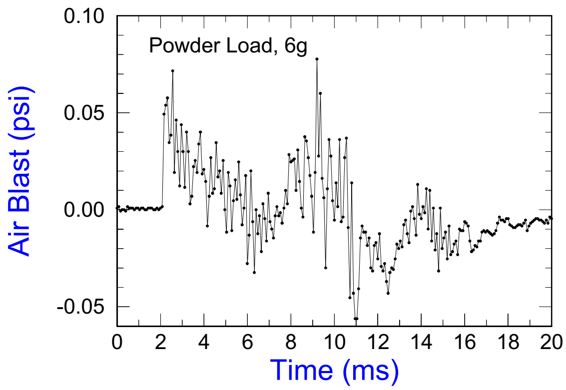

Figure 14. An example of the random oscillatory fluctuations typically seen in air blast profiles from light powder loads. (For conversion to SI Units, 1 psi = 6.89 kPa.)

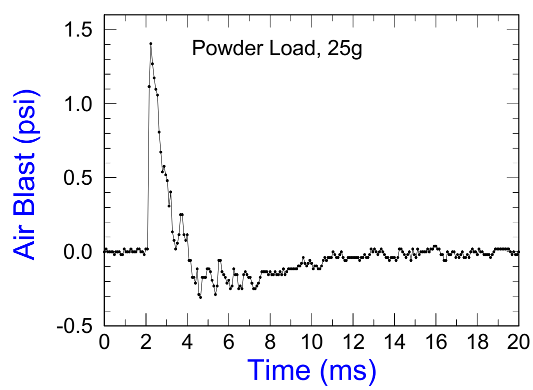

Figure 15. An example of an air blast profile for a heavy powder load. More closely resembling that of a typical explosion (see Figure 12). (For Conversion to SI units, 1 psi = 6.89 kPa.)

the air blast profile still retains some general features of the shape of the internal pressure profile, see Figure 13. (Note that the time delay before the onset of the blast pressure event is due to the time taken for the blast wave to reach the detector. Also, the air blast profile has a negative phase, not seen in the internal pressure profile.) This similarity between the two profiles can only be possible if the so called "shocking up" process, which acts to produce the standard air blast wave shape, has not been completed by the time the blast wave arrives at the detector.

In addition to the air blast profiles tending to reproduce the internal pressure profiles, there is another cause of concussion mortar blast profiles appearing different from that of an explosion. For light powder loads (<12 g), there tends to be random oscillatory fluctuations in the air blast profile, see Figure 14. From the many other measurements made during this and previous studies, it is certain that the fluctuations are not the result of instrument or electrical noise. Further, these random oscillations essentially disappear for heavy powder loads (>20 g). The frequency of the fluctuations is high enough that it may possibly be the result of pressure oscillations occurring within the bore of the explosion chamber, perhaps combined with aliasing because of the fairly low data sampling rate (12,500 samples per second). The combination of internal pressure peak narrowing and the reduction of the oscillatory fluctuations for heavier powder loads, results in pressure profiles that appear much like those of typical explosions, see Figure 15 (compare with Figure 12).

The full set of air blast results is presented in Table 5. Because of the presence of significant random oscillatory fluctuations in many of the air blast profiles, the rapid rise of many others, and because it is the duration of the positive phase of the blast wave that is of interest, it was felt that attempts to determine the FWHM would be difficult and of little value. Accordingly, for each profile, only an estimate of the duration of the positive phase was made. However, in some cases it was necessary first to mentally smooth the profiles to be able to pick the end point of the positive phase of the blast wave. Figure 16 is a graphical presentation of air blast impulse as a function of concussion powder load mass.

Discussion

Internal pressure

Based on fundamental principles, much of what was observed in these measurements might have been predicted, at least in a general way. For example, over the range of concussion powder loads, internal mortar pressure increases with load mass, but it is not strictly proportional to load mass, particularly for light loads. That is to say, it would be expected from basic principles that internal mortar pressure would be greater for a 6 g load than for a 3 g load. It would also be expected that internal pressure for a 6 g load

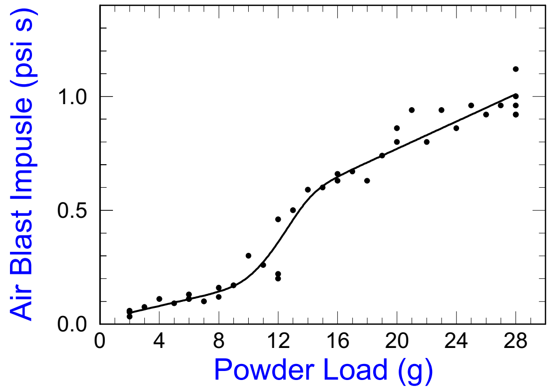

Figure 16. A graph of time integrated air blast (pressure impulse) as a function of concussion powder load mass. (For conversion to SI Units, 1 psi = 6.89 kPa.)

would be more than twice that for a 3 g load. Indeed, for some very small loads, it would be expected that the powder would burn without producing any detectable pressure event, particularly for a nitrate-based flash powder.

This study was particularly interesting for the authors, because there were a number of unexpected observations, for which the authors presently do not have satisfactory explanations. For example, while it might be expected that there would be a general narrowing (in time) of the internal mortar pressure profiles as powder loads are increased, it would not have been predicted that the narrowing would occur rather precipitously, over a relatively small range of loads (refer to Figure 7). Indeed, the data is fairly consistent with there being two essentially constant profile widths, one about 7 ms and one about 2 ms, with a fairly rapid transition between the two profile widths, occurring at loads of about 11 g of concussion powder. More unexpected was the observation that the wide internal mortar pressure profiles often consisted of a number of individual peaks (see again Figures 5 and 6). Presumably, this is an indication of some type of instability in the burning of light powder loads, but what would cause such instability? What is observed seems like multiple explosions; but would that even be possible, and if so, what is the mechanism that produces such a series of explosions within the concussion mortar?

Table 5. Concussion Mortar Air Blast Data.

Load (g)	Peak Pressure (psi)	Positive Phase (ms)	Impulse (psi·ms)
2	0.015	5.8	0.033
2	0.036	9.0	0.059
2	0.033	9.2	0.053
3	0.092	2.0	0.075
4	0.075	5.1	0.11
5	0.056	6.3	0.092
6	0.078	8.7	0.11
6	0.075	9.6	0.11
6	0.087	5.1	0.13
7	0.073	10.	0.10
8	0.11	4.7	0.16
8	0.096	5.4	0.12
9	0.20	3.4	0.17
10	0.20	4.2	0.30
11	0.23	4.0	0.26
12	0.13	4.6	0.20
12	0.30	4.2	0.46
12	0.13	5.4	0.22
13	0.54	2.2	0.50
14	0.57	2.6	0.59
15	0.75	1.9	0.60
16	0.58	2.9	0.66
16	0.62	3.0	0.63
17	1.12	1.8	0.67
18	0.92	1.6	0.63
19	1.06	1.8	0.74
20	1.17	2.5	0.86
20	0.83	2.3	0.80
21	1.21	1.7	0.94
22	1.13	1.6	0.80
23	1.32	2.1	0.94
24	1.00	1.6	0.86
25	1.40	2.0	0.96
26	1.38	2.4	0.92
27	1.34	2.0	0.96
28	1.40	2.1	0.96
28	1.38	2.1	0.92
28	1.60	2.2	1.00
28	1.63	1.2	0.92
28	1.62	2.0	1.12

(For conversion to SI Units, 1 psi = 6.89 kPa.)

Burst Strength Safety Margin

One reason for this study was to determine the safety margin in the strength of concussion mortars. Perhaps the simplest method to verify that the strength of a device like a cannon (or concussion mortar) provides an adequate safety margin, and a method that has been used for centuries, is to fire the device when intentionally overloaded with powder (a so-called "proof firing"). However, while adequate to the need, this does not give quantitative information on the pressures being developed internally. That is unfortunate, first, because it means that a proof firing cannot quantify the pressure safety margin, and second, because such pressure information is intrinsically interesting. Accordingly, internal pressure measurements were made as part of this study. Using Luna Tech's Concussion Flash Powder, it would appear that the internal mortar pressure for a maximum 28 g (1.0 ounce) load does not exceed 4000 psi (28 MPa) at the bottom of the explosion chamber and less near the muzzle of the mortar. It is important to note that the use of other, more brisant, flash powders would certainly produce much higher internal mortar pressures! Accordingly, the following discussion concerning the adequacy of the strength of concussion mortars only applies to their use with Luna Tech's Concussion Flash Powder.

To calculate the strength safety margin for a concussion mortar it is necessary to first determine its burst strength. For one way to do this, consider the following. Concussion mortars are generally made using a mild cold-rolled steel (such as AISI 1025), the yield strength of which is rated at 6.8×10^4 psi (4.6×10^8 N/m^2).[2] Clavarino's equation[3] can be used to estimate the maximum burst strength of a thick-walled, cylindrical pressure vessel with closed ends (the bottom of a concussion mortar's explosion chamber). Similarly, Birnie's equation[3] can be used for the calculation at the open end of the concussion mortar. When these calculations are performed, using a yield strength as the safe tensile strength of the steel, the result is a maximum burst strength of approximately 3.5×10^4 psi (2.4 MPa). Accordingly, there is a pressure safety margin of more than a factor of eight for the concussion mortar used in this study, when using Luna Tech's Concussion Flash Powder.

Recoil Forces

The recoil forces measured in this study during the firing of a concussion mortar with a full load of powder are in good agreement with the earlier study,[1] especially considering the significantly different test methods employed. In the earlier work, when using Luna Tech's Concussion Flash Powder, it was observed that the recoil, produced upon firing the mortar in a downward direction, was sufficient to raise a 25 pound (11.4 kg) mortar, 8 inches (0.20 m) into the air. This corresponds to an initial upward velocity of 6.6 feet/s (2.0 m/s). When using the impulse measured in this study for the concussion mortar fired on a concrete slab, an initial upward velocity of 7.9 feet/s (2.4 m/s) would be produced for the same mortar mass. This value is only 20% higher.

The recoil forces recorded in this study (as high as 5500 lbf), probably appear to some readers as being quite high. However, it is important to remember that these high forces are being applied for less than 2/1000 of a second. This is the same impulse and similar force that would be produced by dropping a hard 25-pound (11.4 kg) object from a height of one foot (0.3 m). Further, should it be necessary, the peak recoil force can be significantly reduced (e.g., by 66%) by simply placing the concussion mortar on a soft surface such as carpeting (refer to Table 4). Note that the use of carpeting under the mortar is also energy absorbing, as indicated by the 22% reduction in impulse.

Air Blast

The shape of the air blast pressure profile, under the conditions of these measurements, is not the same as those from typical explosions (refer to Figures 12, 13, and 14). As a result, the scaling equations used to predict blast pressures at various distances from an explosion may not be reliable. Accordingly, a more complete discussion of the expected effects of concussion mortar firing on human hearing should be delayed until more complete test data has been assembled. However, comments can be made regarding sound levels at the distance used in this study, 5.8 feet (1.8 m). For the full-recommended powder load (1.0 ounce or 28 g) of Luna Tech's Concussion Flash Powder, the maximum measured air blast pressure was approximately 1.6 psi (11 kPa). It is reported that upon exposure to a blast pressure of 15 psi approximately half the population will suffer rupture of the ear drum (tympanic membrane); at 3.2 psi, approximately 1% will experience rupture of their ear drums.[4] Further, the threshold for ear drum rupture is reported to be in the range of 2 to 4 psi.[4] Accordingly, there would seem to be no possibility of rupturing ear drums under the conditions of this study.

Ruptured eardrums are not the only concern relating to noise induced hearing loss. There can also be temporary and permanent loss in hearing acuity (referred to as baseline shifts). The government and various researchers have set different criteria for what degree of hearing loss is acceptable. For example, in the work place, US OSHA has established a maximum impulsive noise limit (explosive-like sounds) of 140 dB fast response.[5] The military has established that it is acceptable for exposure to 100 impulsive noise events (weapon firings) per day, where the maximum acceptable sound level is roughly150 dB.[6] At the distance used in this study, a sound level of 150 dB should be observed for loads exceeding approximately 6 grams.

Graphing internal mortar pressure and recoil force as impulse (time-integrated pressure and force) produced straight lines, effectively eliminating the effect of varying peak width. However, when this was done for air blast pressure, there is an obvious break in the curve at about 12 g loading mass (refer to Figure 16). In effect, powder loads greater than about 12 g are disproportionately more effective at producing an air blast than are loads less than about 12 g. This might possibly be the result of some type of increased efficiency in the explosive burning of the concussion powder inside the mortar. However, if that were the case, a similar break would also have to be present in the impulse curve for internal pressure, and no such break occurs (refer to Figure 9). A more likely explanation is that the added blast is being produced outside the mortar. Recall that the concussion flash powder used in these measurements is quite fuel rich (approximately 1.5 times the stoichiometric amount of magnesium). Most of this excess fuel must surely burn as it mixes with oxygen from the air. If the mixing is thorough and fast, it is possible (likely?) that the burning will be explosive, contributing to the production of air blast. To account for the near step-wise increase in air blast observed in the present study, two things would have to be the case. First, only medium and heavy powder loads must meet the requirements for explosive air burning; and second, there must be a rapid onset of conditions leading to explosive air burning. Although the authors do not have a satisfactory physical explanation for the observed near step-wise increase in time integrated air blast, based on the vast experience of one of the authors using this type of concussion flash powder, it is felt that explosive air burning is the most likely explanation.

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