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Repeat Firing of 10.2 cm (4 in.), SDR–17, HDPE Mortars

K.L. Kosanke and B.J. Kosanke
PyroLabs, Inc., 1775 Blair Road, Whitewater, CO 81527, USA

ABSTRACT

High Density Polyethylene (HDPE) mortars are beginning to find wide use because of their desirable characteristics. They are relatively inexpensive, lightweight, have a long service life, and some consider them to be among the safest mortars presently in use. Initially HDPE mortars were only recommended for use in electrically fired displays, where each mortar is fired only once. This was done because of a desire to take a cautious approach with this relatively new mortar material, even though the mortars had successfully passed some repeat firing tests. Now, it is becoming increasingly common to use HDPE mortars for manually discharged displays, in which individual mortars are fired repeatedly. The mortars heat up during firing, and, being a thermoplastic, they lose strength with increasing temperature. If mortar temperature rises sufficiently high, they will burst during use, venting the lift gases needed to propel shells to safe altitudes. To date there has been no systematic study of HDPE mortars under conditions of repeat firings, in order to determine the safe limits for their use. Thus it is appropriate to more carefully examine the performance of HDPE mortars under conditions of repeat firing and to offer guidance for their use. Measurements were made of the thermal energy deposited in a mortar during the process of firing 10.2 cm (4 in.) aerial shells and of the distribution of that thermal energy along the length of mortars for typical aerial shell firings. Then, measurements were made of the rate of heat dissipation from HDPE mortars freely exposed to air and when buried in dry sand. Finally, data was collected regarding the ability of HDPE mortars to survive shell firings as a function of temperature. With this information, very rough guidelines are proposed for repeat firing of thick-walled, 10.2 cm (4 in.), SDR–17, HDPE mortars.

Introduction

The use of High Density Polyethylene (HDPE) for fireworks mortars has been independently discovered by several individuals around the world. For example, S. Howard of Australia sets the date of his first use sometime before 1970,[1] R. Lancaster of Great Britain reports his use as beginning about 1976,[2] and P. Spielbauer and the authors first use in the United States dates to about 1985.[3] However, most people in the fireworks industry were probably unaware of the potential of HDPE mortars until articles describing their use began to appear in the mid to late 1980s.[4,5,6]

Initially the authors limited their endorsement of HDPE mortars to use in electrically fired displays, where each mortar fires only once during a show. Since then, the use of HDPE mortars has become fairly widespread, and they are now being used with increasing frequency in manually fired displays. With repeated shell firings over a short interval, the mortar's interior surface can heat to temperatures exceeding 100 °C (212 °F). Since it is known that the strength of HDPE falls with increasing temperature, at some temperature, the mortar's strength must fall to an unacceptably low value. At that point, use of the mortar must be interrupted until the mortar cools to a sufficiently low temperature.

In an attempt to determine the safe operating temperature for HDPE mortars and to set guidelines for their use when fired repeatedly, the authors undertook the present study. However, in order to limit the scope, the initial work has only been to establish the experimental method to be used in future studies and to briefly examine repeat firing of 10.2 cm (4 in.) mortars with fairly thick walls (pipe with an SDR of 17). It is anticipated that the present work will soon be expanded and will include other wall thickness and other mortar sizes.

Background Information

Aerial shells are propelled from a mortar because of the gas pressure produced by burning the black powder lift charge. It is the function of the mortar to successfully contain these high pressures while the shell is being discharged. Ignoring end effects, a pipe's strength is a function of its wall thickness, the safe tensile strength (yield strength) of the material from which it is constructed and the inside diameter of the pipe. This functional relationship for thin-walled pipe is shown in Equation 1.[7,8]

$$P_b = 2 \cdot S_t \cdot t_w / d_i \qquad (1)$$

where,

- P_b is burst strength (pressure),
- S_t is safe tensile strength of the pipe material,
- t_w is wall thickness, and
- d_i is the inside diameter of the pipe (occasionally the more conservative outside diameter is used.).

From Equation 1, it is apparent that burst strength for a pipe is proportional to its wall thickness. Thus it is appropriate to consider the wall thickness for typical 10.2 cm (4 in.) HDPE mortars; these are listed in Table 1.

Equation 1 also identifies burst strength as proportional to the safe tensile strength (yield strength) of the pipe material. High Density Polyethylene resin type PE–3408 has the highest rated tensile strength commonly available. Thus this is the resin type of choice, and the one used for mortars in this study.

The use of HDPE for fireworks mortars pressure-stresses the pipe in a substantially different manner than typical plumbing applications. Probably the most significant difference is the very short duration of the pressure generated by shell firings, typically less than about 0.03 seconds.[9,10]. This is less than one 10-billionth the time of a typical plumbing application. The resiliency of HDPE, coupled with the very brief interval of the pressure pulse from shell firings, seems to provide it with significantly greater strength than would be predicted from Equation 1.[10]

HDPE is a thermoplastic (i.e., it melts at high temperature); thus its strength diminishes as temperature rises. The temperature-rating factor for HDPE pipe is its relative strength as a function of temperature in typical plumbing applications. Figure 1 illustrates the effect of temperature on the burst strength of HDPE pipe.[11] As can be seen, the strength factor has been normalized to 1.0 at 23.9 °C (75 °F), and it falls by 10% for every 7.2 °C (13 °F) rise in temperature. Figure 1 is greatly simplified and not a completely accurate representation of the manner in which HDPE pipe loses strength with increasing temperature. Nonetheless, it clearly suggests that the strength of HDPE mortars must fall to dangerously low levels as their temperature rises. With each shell fired, the mortar absorbs a portion of the thermal energy released from the burning Black Powder; this manifests itself as a rise in the temperature of the mortar. Thus, unless the mortar is allowed to cool between repeated shell firings, the mortar will lose strength with each firing, as its temperature rises.

Table 1. Wall Thickness for Typical 10.2 cm (4 in.), HDPE Mortars.

Source – Designation	Minimum Specified Wall Thickness		Typical Wall Thickness[c]	
	cm	(in)	cm	(in)
Commercial Pipe – SDR = 17[a]	0.67	(0.26)	0.74	(0.29)
Mighty-Mite Molded Mortar	n/a	n/a	0.66[b]	(0.26)
Commercial Pipe – SDR = 21[a]	0.54	(0.21)	0.58	(0.23)

Notes:

[a] SDR stands for Standard Dimensional Ratio and equals the pipe outside diameter divided by the minimum wall thickness.

[b] Mighty-Mite Mortars have a wall that varies in thickness, grading from thickest at the bottom to thinnest at the top. The value reported is for 8.9 cm (3.5 in) above the bottom.

[c] Manufacturers tend to extrude HDPE pipe with walls that exceed the minimum specified thickness. The thickness reported here are those measured on the mortars used in this and future studies.

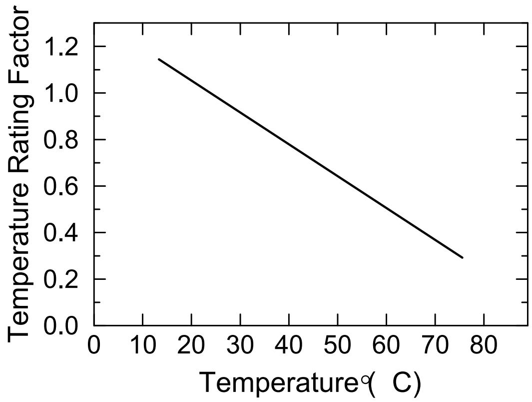

Figure 1. Temperature rating factor for HDPE pipe, derived from Reference 11.

Experimental method

The first portion of this study was conducted to learn how measurements should be made. One piece of information needed was, how long after thermal energy (heat) is deposited on the inside of a mortar does it become evenly distributed throughout the wall of the mortar? This information was needed to design intelligent shell firing and temperature measuring sequences. Another piece of information needed was, at what point on the mortar does the highest temperature occur? This is the point where the mortar is most likely to fail and where the temperature needs to be monitored most closely. Finally, in preparation for destructive testing, what method should be used to raise the temperature of the mortars to near their failure temperature?

In the second portion of this study, the basic data needed to help establish the safe limits for repeat firing was collected. This consisted of determining: how much thermal energy is deposited in the mortar with each shell firing; what is the rate of heat loss from the mortar as a function of mortar temperature and its environment, and what is the mortar temperature at which failures could be expected to occur for typical spherical and cylindrical shells.

Finally, based on the data collected, rough guidance was offered for safe limits of repeat firing of 10.2 cm (4 in.), SDR–17, HDPE mortars.

Tests and Measurements

Thermal Equilibration Time

When an aerial shell is first fired from a mortar, the inside of the mortar is very hot and the outside has not begun to warm-up. As time passes, heat energy is distributed more evenly throughout the wall. Eventually, if essentially no energy is lost from either the inside or the outside of the mortar, the temperature will be the same at every point in the wall. The first measurement in this study was of the time required to distribute the thermal pulse from a shell firing throughout the wall of the mortar. This was needed to establish the appropriate time delay after shell firings before other measurements could reliably be made. It was also needed to design the shell firing sequences for some of the tests that would follow.

For an HDPE mortar, the time it takes to reach thermal equilibrium is a function of wall thickness, with thicker walls requiring longer times to equilibrate. Thus, the thickest-walled mortar (commercial pipe with SDR–17) was examined first. For this determination, a single thermocouple was attached to the exterior of the mortar, a few centimeters above its mortar plug. The thermocouple was attached with a narrow strip of PVC tape. Then the mortar was loosely wrapped with fiberglass insulation and mounted in an enclosure to hold the mortar and prevent drafts from affecting the measurement. At this point, the mortar was ready for a series of test firings. After each firing, a plug was inserted into the mouth of the mortar to reduce thermal loss (from convection) from inside the mortar. Each measurement consisted of monitoring the temperature rise of the exterior of the mortar as a function of time. The data from a series of tests are shown in Figure 2 as the percent of maximum temperature reached.

As can be seen, the maximum temperature is reached in about two minutes and certainly within three minutes. At that time, it is assumed that the mortar has reached essentially a constant temperature throughout the thickness of the wall. In the data reported below, if a time after firing is not given for a temperature measurement, that time is approximately three minutes.

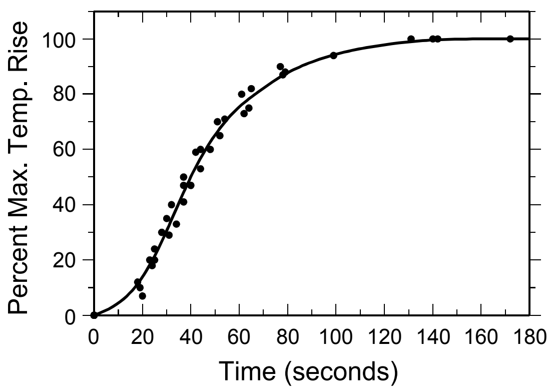

Figure 2. HDPE mortar warm-up curve from test firings of aerial shells.

Distribution of Thermal Energy along the Length of a Mortar

All else being equal, the most likely point of failure for an over-heated HDPE mortar will be where it is hottest. Thus it is important to examine the distribution of temperature along the length of a mortar to determine where the temperature is highest.

For this determination, a series of six thermocouples were attached along the length of the test mortar (SDR–17). Attachment points were at 0.0, 2.5, 7.6, 15.2, 27.9, and 45.7 cm (0, 1, 3, 6, 11, and 18 in.) above the mortar plug, which was made of 3.8 cm (1.5 in.) thick wood. Thermocouple attachment was again made using narrow strips of PVC tape. Then the mortar was loosely wrapped with fiberglass insulation and mounted in an enclosure to hold the mortar and prevent drafts from affecting the measurements. At this point, the mortar was ready for a series of test firings. After each firing, a plug was inserted into the mouth of the mortar to reduce thermal energy loss. Each measurement consisted of recording the exterior temperature of the mortar approximately three minutes after the test firing.

Both spherical and cylindrical test shells were used. Spherical shells were tested with and without a lift cup, to raise the shell above the bottom of the mortar; also, both 2F-A and 4F-A Black Powder were used for lifting spherical shells. Table 2 lists the various shell and lift configurations used.

Test results are summarized in Figures 3, 4 and 5, where each data point is the average result from

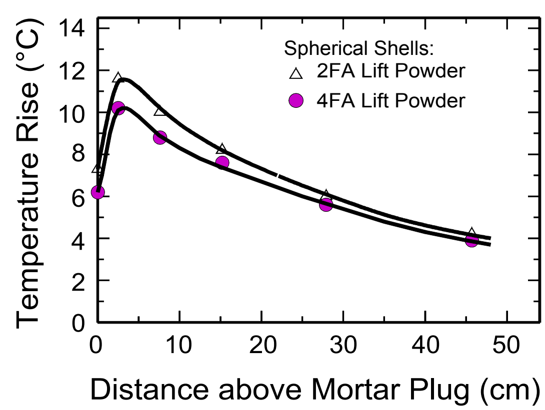

Figure 3. Average mortar temperature profiles for spherical test shells without lift cups.

Table 2. Test Shell Configurations Used in Determining Mortar Temperature Profiles.

Shell					Lift			Dead Volume	
	Mass		Diameter			Mass		[a]	
Type	g	(oz)	cm	(in.)	Type	g	(oz)	cm^3	(in^3)
Sph.	363	(12.8)	9.4	3.7	2F-A	28	(1)	345	(21.6)
	363	(12.8)	9.4	3.7	2F-A	28	(1)	559	(34.1)
	363	(12.8)	9.4	3.7	4F-A	28	(1)	345	(21.6)
	363	(12.8)	9.4	3.7	4F-A	28	(1)	559	(34.1)
Cyl	500	(17.6)	9.2	3.6	2F-A	55	(2)	257	(15.7)

[a] Dead volume is the space below an aerial shell when resting in a mortar. Dead volume affects the maximum mortar pressure and the distance above the bottom of the mortar where maximum mortar pressure is reached. For more information about pressure profiles and the effect of dead volume, see References 9 and 12.

at least three test shell firings. Figure 3 presents the mortar temperature profiles for spherical shells fired without a lift cup (dead volume = 345 cm^3) when using 4F-A and 2F-A Black Powder. Figure 4 presents the results for spherical shells with lift cups (dead volume = 559 cm^3), and Figure 5 presents the results for cylindrical shells.

The curves in Figures 3, 4 and 5 should only be considered approximations of actual mortar temperature profiles. This is because only a limited number of tests were averaged together and only a limited number of thermocouples were used near the bottom of the mortar where the profile is rapidly changing. Nonetheless, the curves are quite consistent and appear essentially as expected. For example:

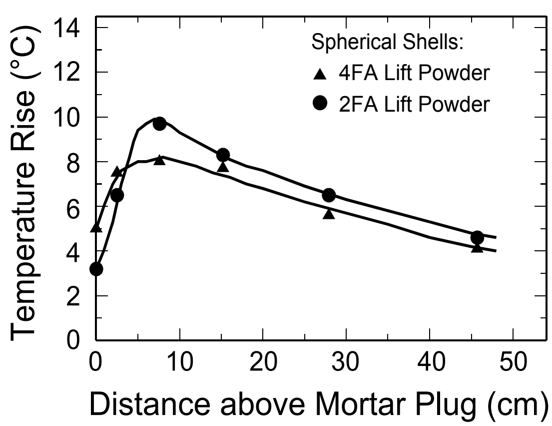

Figure 4. Average mortar temperature profiles for spherical test shells with lift cups.

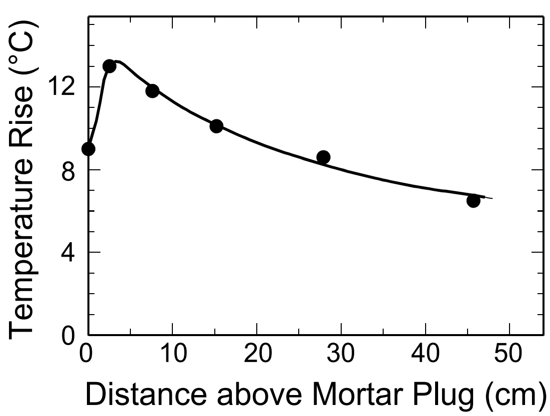

Figure 5. Average mortar temperature profile for cylindrical test shells.

1. Mortar temperature slowly increases as one proceeds along the length of the mortar toward the bottom. Presumably, this is because as one moves down the length of the mortar, it has been exposed to the high-pressure lift gases for longer periods of time. (The amount of thermal energy transferred to the mortar is a function of both the temperature and the pressure of the lift gases, and the duration of that exposure.)
2. The mortar temperature suddenly decreases just before reaching the plug. Presumably this is because some of the heat initially deposited there has been conducted away. (The test mortar was closed on the bottom with a wooden plug, which, along with the mortar wall below the top of the plug, constitutes a heat sink.)
3. The distance above the plug to where maximum temperature occurs is roughly proportional to dead volume. Presumably this is because as dead volume increases more of the mortar just above the plug receives the maximum exposure to the hot lift gases, with the effect that the point of greatest average exposure moves upward.
4. The maximum temperature detected is greatest for cylindrical shells, followed by spherical shells without a lift cup, and is least for spherical shells with a lift cup. Presumably this corresponds to the relationship for expected mortar pressures for those types of shells. (The amount of thermal energy transferred to the mortar is a function of the pressure of lift gases.)

In the following results, a point 5.1 cm (2 in.) above the mortar plug was chosen for measurement of maximum mortar temperature.

Method for Pre-Heating the Test Mortars

It might seem that the best way to heat HDPE mortars to near their failure temperature, in preparation for determining the conditions resulting in their failure, would be to repeatedly fire shells from them. One obvious problem with this is the expense of preparing the large number of test shells, which would be considerable. However, there are other technical and operational problems. For example, the amount of thermal energy deposited in the mortar during test firings of identical shells seems to vary significantly from shot to shot. Figure 6 presents the results from six test firings of spherical shells with lift cups and using 4F-A lift powder. The temperature rise for each thermocouple is shown for each test. The gridded area illustrates the range of values observed.

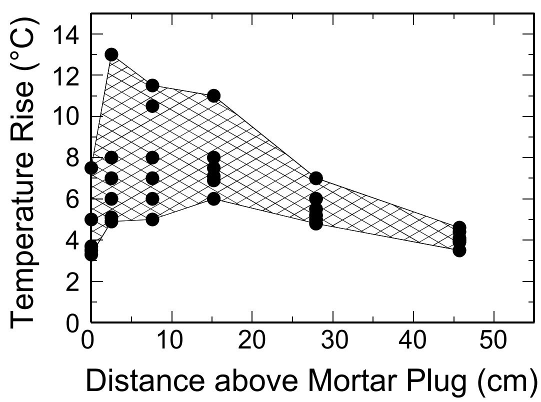

Figure 6. Range of mortar temperature values observed during test shell firings. [Spherical shells with 4F-A lift powder and with lift cups.]

At present, the authors do not fully understand the reason for the range of measured temperatures in the above tests. However, it is likely that it is related to the dynamics of the gas flow in the mortar during its firing. It is possible that much of the variability is merely an artifact caused by only measuring temperature at a series of points along one side of the mortar. The authors speculate that when a shell is propelled up the mortar, it moves somewhat from side to side, within the constraint imposed by the walls of the mortar. As it follows this zigzag path, the gap between the shell and mortar varies from place to place and moment to moment. As a result, the amount of high temperature lift gas escaping between the shell and the wall varies in similar fashion. If this is the case, then it is likely that the amount of thermal energy received by the mortar wall at various points depends on the details of the shell's motion within the mortar, which will be different for each shell firing. Thus if measurements are made along a line of points up one side of the mortar, it seems likely that significant variations from shot to shot could be expected.

Partially as a test of the above hypothesis, but primarily to find a more predictable method of heating mortars, another series of measurements were made. In these tests, bags of lift powder, without attached test shells, were placed in the test mortar and fired. The results from these tests are shown in Figure 7. On average there was slightly less thermal energy transferred to the mortar, but the most striking difference is that the values for the points are more closely grouped. For this reason, plus the cost savings from firing only lift powder and not test shells, it was decided to preheat test mortars by repeatedly burning bags of lift powder in them. So-called B-blasting powder (sodium nitrate oxidizer) is slower burning and was found to produce greater mortar temperature increases than normal A-blasting powder (potassium nitrate oxidizer). The average temperature rise for 28 g (1 oz) of 4F-A powder is about 7 °C (13 °F), while that for 1F-B powder is about 37 °C (66 °F). Thus B-blasting powder was chosen to preheat the test mortars.

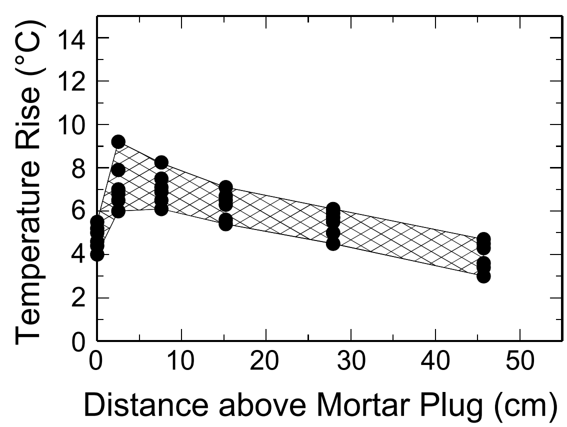

Figure 7. Range of mortar values observed during test burning of bags of lift powder alone [28 g (1 oz) of 4F-A lift powder].

Amount of Thermal Energy Deposited in Mortar during Shell Firing

The data needed for this determination, is the same as already reported to establish the mortar temperature profiles shown in Figures 3, 4 and 5. Knowing the temperature rise of an object, its mass, and its heat capacity (specific heat), it is a simple matter to calculate the amount of heat (thermal energy) absorbed, see Equation 2.

$$q = m \cdot C \cdot \Delta T \quad (2)$$

where,

- q is the heat transferred in calories,
- m is the mass of the object in grams,
- C is the heat capacity in cal/g °C (0.50 cal/g °C for HDPE[13]), and

ΔT is the change in temperature in °C.

Considering a 1-cm^2 section of a SDR–17 mortar, with a typical wall thickness of 0.74 cm [Table 1], and given that the density of HDPE averages[13] 0.95 g/cm^3, the heat required for a 1 °C (1.8 °F) temperature rise is 0.35 calories. The maximum temperature rise seen in the various profiles shown in Figures 3, 4, and 5, averages about 10 °C (18 °F) for spherical shells and about 13 °C (23 °F) for cylindrical shells. The thermal energy deposited in the mortar at the point of maximum temperature rise is approximately 3.5 and 4.5 cal/cm^2 for spherical and cylindrical shells, respectively.

As an aside, it was felt that it might be of interest to determine the fraction of thermal energy, which is produced by burning the Black Powder lift that is absorbed by the mortar. This was calculated by mathematically dividing the mortar into six sections of varying length, one section centered on each thermocouple. Then, assuming the temperature rise of each section was that observed by the thermocouple, Equation 2 was used to calculate the heat deposited in that section. The total thermal energy absorbed was determined by summing the individual values. This resulted in estimates that, typically, the mortar absorbs 1.2 and 1.6 kcal of energy when firing spherical and cylindrical shells, respectively. Knowing the amount of lift powder used, and that the heat of reaction for Black Powder[14] is 0.66 kcal/g, the total heat produced was calculated. This amounts to about 18 and 36 kcal for spherical and cylindrical shell firings, respectively. Thus the mortar absorbs approximately 6.7 and 4.4 percent of the total thermal energy produced by the lift powder during the firing of spherical and cylindrical shells, respectively.

Rate of Thermal Energy Loss from Mortars

Thermal energy always migrates from hotter to cooler areas, and the rate of heat transfer is a function of the temperature difference (temperature gradient) between the two areas. Thus in the examination of the heat loss from mortars, the rate of loss was always considered in terms of temperature gradients, and not specifically in terms of mortar and environment temperatures. This provides solutions that are more generally applicable, instead of requiring data for each different mortar and environmental temperature.

There are three mechanisms for transferring thermal energy: radiation, convection, and conduction. For above ground mortars, only convection is significant; the hot mortar is in contact with cool air, which acquires heat from the mortar and then drifts away. For buried mortars, only conduction is significant; the hot mortar is in contact with the cool ground, which acquires heat from the mortar and passes it from layer to layer through the ground. Heat transfer problems are often fairly simple to solve analytically; however, in this case there are complexities that make an analytic solution impractical and possibly unreliable as well. Thus an empirical approach has been taken. For this, mortars were instrumented with thermocouples at six locations, attached in the manner described above. However, for above ground mortars, a rubber band was placed around the mortar and over the thermocouple to augment its attachment. This was necessary because, at the temperatures during testing, the adhesive on the tape failed to provide sufficient attachment strength. The test mortar was then placed in the environment to be studied.

To study above ground mortars, a stake was used for mortar support. The mortar was attached to the stake so as not to interfere with or distort the temperature measurements. Shields were erected around the test mortar to shade the mortar from direct sunlight and breezes. However, the shields were not close enough to restrict free air circulation around the mortar. At this stage of work, no attempt was made to account for effects that would be produced by having mortars in racks. (Racks would restrict air circulation to some extent, insulate some spots on the mortar, and may place heated mortars close to one another.)

To study buried mortars, a wooden box was used to support the mortar. The box provided about 16 cm (6.5 in.) of space around the mortar; the space was filled with dry sand. (Hopefully, data will eventually be collected using wet sand, which will have greater thermal conductivity and a higher heat capacity.)

To begin the process of taking measurements, the mortars were heated by burning packets of Black Powder in them. The packets were small enough and their burning separated enough in time so as not to damage the mortar by localized over-heating. Generally, 28 g (1 oz) packets of 1F-B powder were used, with two minutes elapsing between burnings. Figure 8 is an example of the temperature history recorded by thermocouple number two (TC2) in one above ground thermal energy loss experiment.

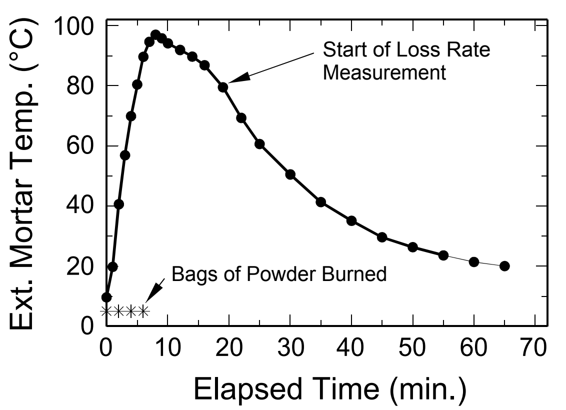

Figure 8. Temperature history recorded by TC2 for an above ground HDPE mortar.

It is at the approximate location of TC2 and TC3 where the mortar is hottest and is expected to fail during use. Thus this is where attention was focused. Figure 9 presents the results from one of three above ground tests. Here, temperature gradient is the difference between mortar exterior and air temperatures. The rate of heat loss is reported as temperature loss rate because the two are proportional (see Equation 2) and because this information will be of more direct use later in this report.

It appears that the temperature loss rate at TC2 and TC3 is a linear function of temperature gradient. Also the loss rates at TC2 and TC3 is similar,

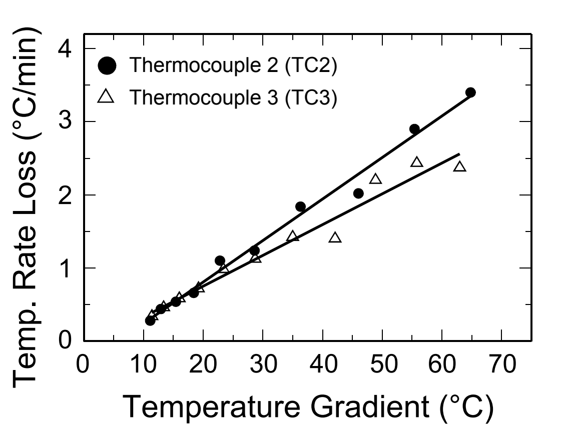

Figure 9. Temperature loss rate at TC2 and TC3 for an above ground HDPE mortar.

but not precisely the same. Considering that the mechanism for heat loss is convection, it is not surprising there is a difference and that the rate of heat loss at TC3 is less than at TC2. The heat being convected away from near TC2 would be expected to raise the air temperature over TC3 higher than ambient air temperature, thus reducing the efficiency of heat loss at that point.

Of necessity, the rate of temperature loss (heat loss) must be zero when the temperature gradient is zero. However, the Y-intercept for the lines in Figure 9 are about –0.3 °C/min. It is believed that this is an artifact of fitting the data to a linear relationship and not including data for near zero temperature gradients. Nonetheless, in the temperature gradient range of greatest interest, this should be of no concern.

When Figure 9 results were compared with those of earlier experiments, it was observed that the temperature loss rate had fallen about 20 percent for the same mortar (see Figure 10). Upon examination of the mortar, apparently a scale of combustion products had built up on the interior mortar walls. While the direction of the change is what would be expected, its magnitude is larger than would have been expected. Thus, in predicting the safe limits for repeat firing, it seems that the cleanliness of the HDPE mortar also must be considered. The temperature loss rate (R_{TL}) for a clean mortar, shown in Figure 10, is:

$$R_{TL}\ (°C/min) = 6.7 \times 10^{-2} (\Delta T) - 0.16 \qquad (3)$$

For a buried mortar, the rate of heat loss was observed to be almost exactly the same for both TC2 and TC3, see Figure 11. When compared with above ground mortars, the most significant difference is that the temperature loss rate is only about one-third as much for the same gradient. Also different is that the relationship is not linear, the curve is very nearly a parabola and the temperature loss rate is given in Equation 4.

$$R_{TL}(°C/min) = 5.0 \times 10^{-4} (\Delta T)^2 \qquad (4)$$

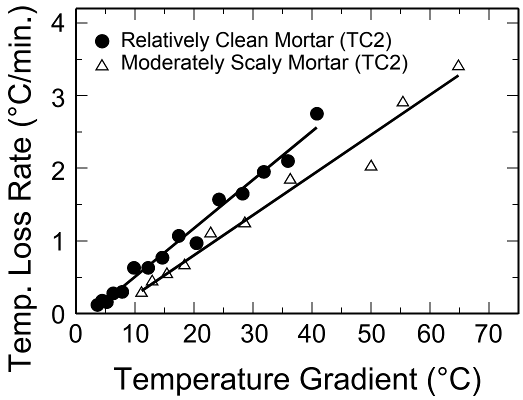

Figure 10. Temperature loss rate as a function of cleanliness of an above ground mortar.

With above ground mortars, because even minor air currents continually carry heated air away, the ability of the air to absorb thermal energy does not diminish with time. However, this is not the case for buried mortars, where the ground nearest the mortars tends to become saturated with heat. To examine this effect, a series of three thermal energy loss experiments were conducted, one immediately following the other, see Figure 12. Using this data, three loss rate curves were derived illustrating that the ability of the ground to absorb heat diminishes with each cycle, see Figure 13. This is an effect that must be considered when attempting to define limits for repeat firing of buried HDPE mortars.

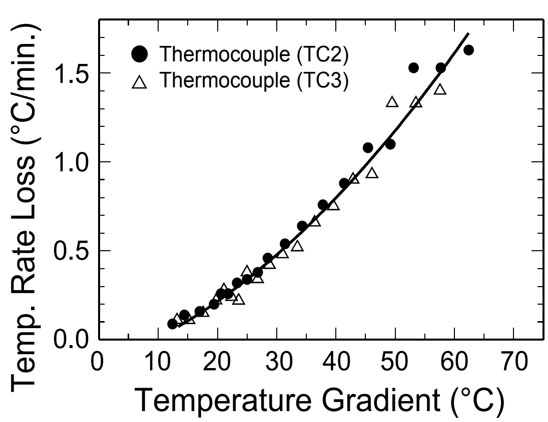

Figure 11. Temperature loss rate at TC2 and TC3 for a buried mortar.

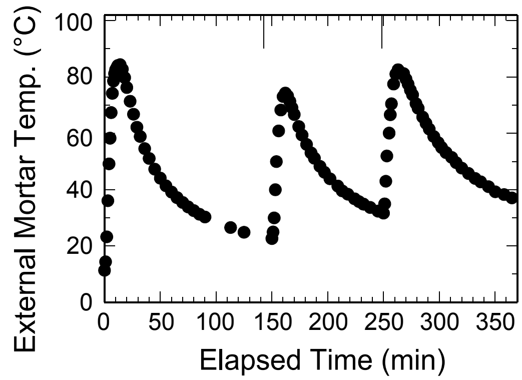

Figure 12. Three consecutive temperature loss rate experiments for a buried mortar.

Failure Temperature of HDPE Mortars

For these measurements, two mortar configurations were used. In some tests, the mortar was insulated, essentially reducing the rate of heat loss to zero. This represents the extreme case of completely thermal-saturated ground. In other tests, the mortars were not insulated and were exposed to cool air, 0 °C – 20 °C (30 °F – 70 °F). In these tests, the mortars were preheated to near their expected failure temperatures; then aerial shells were fired to test whether the strength of the mortars had remained high enough to survive. Mortars that survived were heated to still higher temperatures and tested again. This process was continued until each mortar had failed. Because the firing of cylindrical shells pressure-stresses mortars more than spherical shells, information was collected

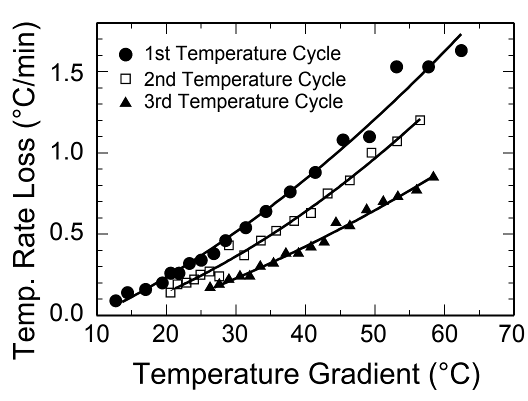

Figure 13. Temperature loss rate at TC2 and TC3 for a buried mortar illustrating the effect of thermal saturation.

Table 3. Survival and Failure Temperatures for 10.2 cm (4 in.), SDR–17, HDPE Mortars.

Shell Type	Maximum Temperature Survived °C		(°F)	Temperature Where Mortar Bulged or Burst °C		(°F)
Spherical	88		(190)	86	[b]	(187)
	99		(210)	88	[b]	(190)
	92		(198)	97		(207)
	102	[a]	(216)	96		(205)
				97		(207)
				108	[a]	(226)
Cylindrical	96		(205)	76	[b]	(169)
	88		(190)	90		(194)
				103	[a]	(217)

[a] The mortar was wrapped in insulation for the test.

[b] The mortar only bulged; it did not burst.

for both types of shells. In this way, data was collected identifying the highest mortar temperature for which mortars survived and the temperatures at which they failed. Results from those experiments are listed in Table 3.

During the tests reported in Table 3, in at least one case, a mortar had visibly bulged, ~0.3 cm (0.12 in.), during preheating. Recall that no significant pressure is produced when bags of Black Powder are burned in the mortars. Thus, the bulging in that one case cannot be attributed to the high pressure of shell firing. In other tests, after the mortars had bulged slightly, they continued to fire shells successfully even though the temperature had been raised significantly. For example, the mortar that bulged at 76 °C (169 °F), while firing a cylindrical shell, continued to withstand cylindrical shell firings at 88 °C and 92 °C. The bulges were small both in terms of change in diameter [~0.3 cm (0.12 in.)] and mortar length affected [~5 cm (2 in.)]. Accordingly, it seems likely that the mortar pressure during subsequent shell firings was about the same as for unbulged mortars. Thus, the survival of the mortar during subsequent firings at higher temperatures probably cannot be attributed to those firings putting significantly less stress on the mortars. At present, the authors do not fully understand the bulging phenomenon.

It might be of interest to note that on average the mortar burst points were 2.9 cm (1.1 in.) above the plug and ranged from 2.2 to 5.5 cm (0.9 to 2.0 in.) above the plug. Based on the estimated point of highest mortar temperature, temperatures reported in Table 3 were recorded at about 5 cm (2 in.) above the mortar plug. The location of the burst points, which corresponds to the point of highest mortar temperature, suggests that a point slightly closer to the plug should be used in future tests.

The overall strength of an HDPE mortar at high temperature depends on the temperature of the pipe throughout the thickness of its wall. As an example of the complexity this introduces, consider the case where the mortar is exposed to relatively cool air on its exterior. In this case, the temperature measured on its exterior wall is a complex function of both the temperature of the mortar, the air temperature, and the degree to which the air is in motion or is stagnant. The data for non-insulated mortars in Table 3 do not consider this complication, and thus must be considered only as a general guide. Based on the work performed to date for 10.2 cm (4 in.), SDR–17, HDPE mortars exposed to relatively cool and calm air, it seems that the maximum service temperature (as measured on their exterior) is not more than about 75 °C (167 °F) for typical cylindrical shells and about 85 °C (185 °F) for typical spherical shells. For insulated mortars, with near zero heat loss, these temperatures are probably about 15 °C (27 °F) higher. For mortars in dry sand (roughly equivalent to dry soil) the rate of heat loss should be somewhere between that for cool air exposed mortars and insulated mortars. Thus, it seems that the maximum service temperature of buried mortars, as measured on their exteriors, would be no more than about 80 °C (176 °F) for typical cylindrical shells and 90 °C (194 °F) for typical spherical shells.

Preliminary Results

The authors feel that the results generated to date are only barely sufficient to suggest even the most preliminary guidelines for repeat firing of 10.2 cm (4 in.), SDR–17, HDPE mortars with wooden plugs. It is only because this subject is of considerable interest to some and has important safety ramifications that an attempt was made to offer any guidance at this time.

During repeat firing of HDPE mortars, some amount of heat will be lost from the mortar between firings. Therefore, a worst-case scenario would be the case of a well-insulated mortar when no heat loss occurred. Thus, if it is determined how many shells of a given type can be successfully fired from an insulated mortar, then surely at least the same number could be successfully fired during a fireworks display. If it is assumed that:

- the initial temperature of the mortar is 20 °C (68 °F);
- only spherical shells of typical weight and normal lift charges are fired;
- the maximum mortar temperature rise produced by these shells is 10 °C (18 °F) per firing;
- the maximum temperature rise for such shells before mortar damage occurs is 100 °C (212 °F) [insulated mortar results]; and
- the thermal energy lost during the process of shell firing, from a non-insulated mortar, provides a sufficient safety margin;

⇒ then it could be concluded that eight typical spherical shells could be rapidly fired from the same mortar without it failing.

If a greater safety margin were felt appropriate, the number of shells could be reduced to seven. For each 10 °C (18 °F) increase in initial mortar temperature, the number of shells should be reduced by one, and conversely, could be increased by one for each 10 °C (18 °F) decrease in initial mortar temperature. Following similar logic, and for similar conditions for cylindrical shells, it could be suggested that as many as five typical cylindrical shells could be safely fired in rapid succession.

Having once raised an HDPE mortar to its limiting service temperature, the question might then be how long to wait between subsequent firings. For above ground mortars, if it assumed that:

- air temperature is 20 °C (68 °F);
- air flow around the base of the mortar is not obstructed;
- adjacent mortars are not hot enough or close enough to affect the mortar of interest;
- the interior of the mortar is fairly free of scale; and
- during repeat firing, because of heat loss during the process, the exterior temperature of the mortar had risen to approximately 70 °C (158 °F), producing a temperature loss rate of a little more than 3 °C (36 °F) per minute;

⇒ then subsequent shells could be fired every three or four minutes.

Following similar logic, and for similar conditions for cylindrical shells, it could be suggested that subsequent cylindrical shells could be fired every four or five minutes.

For buried mortars, the rate of heat loss for the same temperature gradient is about one-third that for above ground mortars. Accordingly, the time between subsequent firings should then be about three-times as long as that for unobstructed above ground mortars with the same temperature gradient.

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