Proceedings Paper:

Langran-Wheeler, C., Barr, A. orcid.org/0000-0002-8240-6412, Clarke, S. et al. (1 more author) (2025) Mitigation of the quasi-static pressure in confined explosions using a surrounding material. In: Proceedings of the 27th International Symposium on Military Aspects of Blast and Shock (MABS27). 27th International Symposium on Military Aspects of Blast and Shock (MABS27), 05-10 Oct 2025, Colmar, France. Military Aspects of Blast and Shock (MABS).

MITIGATION OF THE QUASI-STATIC PRESSURE IN CONFINED EXPLOSIONS USING A SURROUNDING MATERIAL

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Key words: material mitigation, quasi-static pressure, thermal management, confined detonation

ABSTRACT

Surrounding a charge with materials has long been known to alter the blast loading characteristics of the explosion, but the processes involved are not well understood, especially in comparison to the detonation of bare charges. The material's inertial, thermal, mechanical and chemical response influence the blast wave formation and ultimately the output and damage. Identifying the complex mechanisms involved in detonating explosives surrounded by a medium, other than air, is key to understanding their effects and to control the subsequent blast shock and ejecta. Thermal management of the explosive energy output by rapid heat dissipation can greatly dampen the quasi-static pressure (QSP) and combustion of confined events.

High Explosive (HE) tests have been conducted in a confined environment to analyse the mitigation effectiveness of a selection of materials through analysis of the QSP development. A 275-litre unvented chamber instrumented with pressure transducers mounted in the wall was subjected to spherical PE10 charge detonations. Bare and water-mitigated charges are used as a baseline to qualify the effectuality of a range of dry, wet and saturated materials, including vermiculite, perlite and silica. This paper presents the initial findings of the test series and lays out the subsequent testing in the High Explosive Advanced Diagnostics and Media Modelling (HEADaMM) programme.

INTRODUCTION

The detonation of high explosives (HE) within confined environments generates extreme overpressure loading capable of producing severe structural damage and casualties. Confined explosions develop a quasi-static pressure (QSP) as the shock waves of the blast reflect off the surfaces of the space and interact with each other in a cacophony that peters out into an enduring pressure.

The magnitude of this QSP is governed by the energy released during detonation, the total volume of the confinement, and, in some cases, the occurrence of secondary combustion reactions [1]. It can also be reduced by the transfer of the energy out of the gaseous volume, into materials in the environment or the confining material itself, in the form of heat, chemical change or mechanical work.

Where confined detonations present unacceptable risk, mitigation strategies seek to reduce the magnitude of the primary shock front, limit the development of QSP, cool the environment or all three. Placing materials around the charge is commonly used to mitigate the development of QSP [2].

Generic materials such as soil, sand, gravel, and rock reduce transmitted overpressures primarily through compaction, particle rearrangement, and interfacial frictional losses, [3]. Water, employed in bulk layers, sprays, or foams, has demonstrated particular efficacy due to its high density and capacity to absorb mechanical and thermal energy; mechanisms include shock attenuation, cavitation, and vaporisation [4-5].

The mechanisms by which these materials operate can be broadly categorised into three domains. Mechanical energy absorption occurs in porous and granular media through irreversible compaction and particle crushing, converting blast energy into internal work and heat. Momentum transfer involves the redistribution of impulse from the detonation products into a secondary medium, such as bulk water or soil, which is set into motion and thereby reduces the net transmitted impulse of the blast wave. Heat transfer and phase change, most prominent in water-based systems, involve the absorption of thermal energy during heating and vaporisation, thereby reducing flame temperatures and suppressing secondary combustion [6-7]. Collectively, these mechanisms provide a framework for understanding how simple materials mitigate blast effects in confined spaces.

Despite extensive study, the relative importance of these mechanisms remains incompletely resolved. Experimental investigations frequently employ quasi-static pressure (QSP) as a principal diagnostic of blast severity and mitigation effectiveness. As QSP reflects the cumulative effects of reflection, afterburn, and material interaction, it serves as a convenient yet integrative measure of confined blast behavior. However, its sensitivity to confinement geometry, material configuration, and post-detonation chemical kinetics complicates its interpretation [8]. A more precise understanding of how generic mitigating materials influence QSP—whether by absorbing energy, altering momentum pathways, or delaying afterburn—remains essential for advancing mitigation strategies and refining QSP as a reliable experimental metric [9].

EXPERIMENTAL METHODOLOGY

Small scale HE charges were surrounded by mitigant materials and detonated within a confining cylinder; a 1m long steel pipe, Figure 1. The thick-walled pipe had a volume of 275L and was instrumented with three Kulite HKM-375M piezoresistive pressure transducers mounted inside housings with a narrow aperture to protect them.

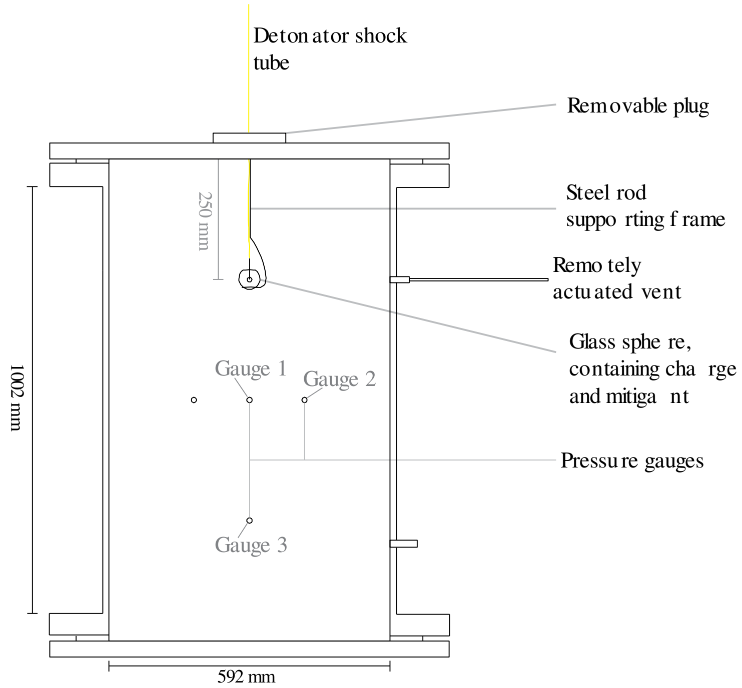

Figure 1: Instrumented chamber cross section

All tests in the series were conducted with 20g spheres of PE10 (84% PETN, 16% binder) plastic explosive. The charges were placed centrally inside open topped glass spheres, nominally 60 mm in diameter, that were supported on a thin steel rod cradle affixed to the end cap. Mitigant materials were placed inside the glass sphere and surrounding the charge, listed in Table 1, chosen based on their known mitigation effects, previous use in literature or their ability to hold water. The charges were initiated by a non-electric detonator in an air atmosphere.

Table 1: Mitigant materials tested.

Tests	**Material**	**Saturation**
T02, T21	Bare	N/A
T03, T22	Water	N/A
T04-09	Vermiculite	Dry, saturated and flooded
T10-11, T19-20	Perlite	Dry and flooded
T15-18	Silica gel	Dry and saturated
T12-13	Fuse sand	Dry
T23-28, T31-32	Sipernat	Dry and moistened
T29-30	Oobleck	Saturated

Vermiculite is well known for its water absorption capability, tested to hold three times its mass in water. Perlite was chosen as a lightweight crushable material in opposition to dense but breakable sand. Silica gel crystals have a high adsorption ability with a vast internal surface area. Also made of silicon dioxide, Sipernat is a lightweight power with a high surface area and absorption and adsorption capabilities. Oobleck is a non-Newtonian fluid made from starch (corn or maize) and water, it has a fluid or solid like response depending on strain rates alongside a high-water content.

The materials were either poured or packed around the charge depending on their nature. ‘Dry’ materials were as delivered with gravimetric moisture contents (μ) of 0.14 for vermiculite and 0.04 for silica gel crystals. Perlite, fuse sand and Sipernat had moisture contents measuring less than 0.01.

‘Saturated’ materials were soaked in water and allowed to drain before being introduced to the glass sphere. ‘Flooded’ materials were soaked in advance and topped off with water in the sphere for the test.

Figure 2: Examples of the mitigant materials packed inside the glass spheres, around the charge. a) water, b) vermiculite, c) perlite, d) silica gel crystals, e) fuse sand, f) Sipernat

RESULTS

The pressure measurements were recorded on a TiePie Handyscope HS6; 16-bit resolution at a sampling rate of 78.125 kHz. The instrumentation was triggered by either a breakwire or off the signal on the central gauge (Gauge 1) with a 20% pre-trigger.

Two of the gauges (1 & 2) were located centrally along the pipe, whilst Gauge 3 was located 750mm from the ignition end cap.

Figure 3 shows the overpressure measurements from Test 21, a bare charge inside a glass sphere. The early time traces indicate the shock waves propagating through the pipe, peaking around 400 kPa whilst the average pressure builds. The longer-term plot traces the development of the QSP through a smoothed average applied with a graduated moving mean. The graduated moving mean was calculated with a 50 point backwards window until T0, 100-point window for the next 3000 samples and a 300-point window for the remainer of the time. This was chosen to best represent the development and longer-term behaviour of the QSP.

The sealed vessel holds the gasses, but the QSP is seen to reduce as heat is lost to the steel and eventually the surrounding environment. To produce a single value for the peak QSP a consistent approach of taking the value at 0.03 seconds was adopted to allow the pressures to stabilise sufficiently and minimise the effects of losses to the pipe. The peak pressure values of T21 are 254.1, 263.2, 261.0 kPa for Gauges 1-3 respectively, averaged for a Peak QSP of 262.9 kPa.

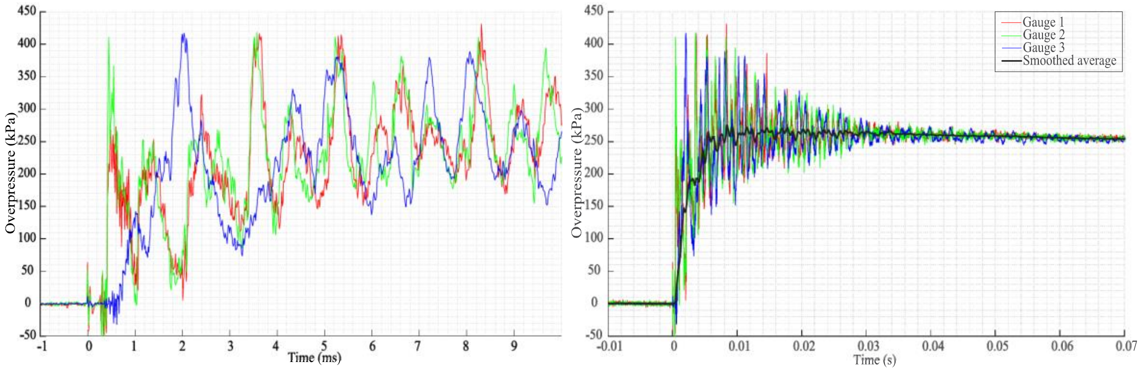

Figure 3: Overpressure measurements of T21, 20g PE10 bare charge in glass sphere. Early time pressure variation and accumulation shown on the left and QSP as an average on the right.

The addition of water as a mitigant causes a prominent reduction in QSP, Figure 4. The Peak QSP is calculated to be 39.4 kPa, an 85% reduction from T21. The initial shocks arrive at the gauges at the same time between tests with a comparable peak pressure but greatly lower energy, showing a negative phase which is not present with the bare charge. The reflection of the blast at the distal end of the pipe returns much less energy, seen by the large reduction of the secondary shock arriving at Gauge 3 and its clear separation from the first.

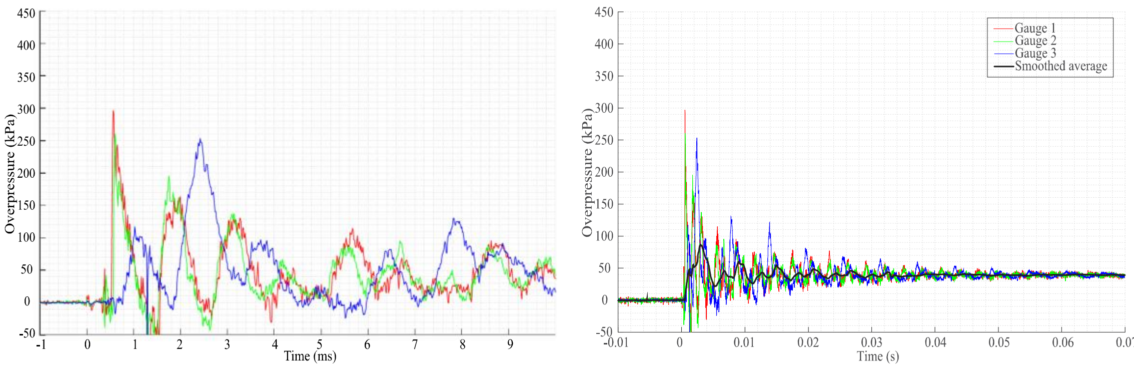

Figure 4: Overpressure measurements of T22, 20g PE10 with 84.3g water mitigation. Early time pressure variation and accumulation shown on the left and QSP as an average on the right.

Table 2 tabulates the initial material conditions and results of all the tests. The mitigant mass (M_m) to charge mass (M_c) ratio and gravimetric moisture content (μ) are displayed as the conditions of the mitigating materials. Gauges providing no data are omitted and marked.

Table 2: Mitigant material properties and Peak QSP test data. Dry (d), Saturated (s) and Flooded (f) marked where required.

Mitigant	**Test**	**M_m/M_c**	**μ**	**Peak QSP (kPa)**			
				Gauge 1	Gauge 2	Gauge 3	Average
Bare	02	0	-	249.1	251.5	-	250.3
	21	0	-	264.1	263.2	261.0	262.8
Water	03	4.12	- (f)	-	38.3	-	38.3
	22	4.22	- (f)	39.3	39.1	39.7	39.4
Vermiculite	04	0.75	0.14 (d)	-	241.1	-	241.1
	05	0.70	0.14 (d)	225.7	224.2	223.3	224.4
	06	3.15	3.01 (s)	42.7	42.2	44.3	43.1
	07	3.30	3.01 (s)	41.6	41.4	41.3	41.4
	08	3.81	4.67 (f)	40.2	39.9	41.3	40.5
	09	4.04	5.10 (f)	39.9	39.1	40.9	39.9
Perlite	10	0.57	0	251.8	250.5	243.9	248.7
	11	0.43	0	252.4	251.7	246.0	250.0
	19	3.00	5.38 (f)	39.8	39.3	41.2	40.1
	20	3.01	6.54 (f)	41.3	40.9	40.9	41.1
Silica gel	15	3.31	0.04 (d)	118.8	118.1	117.7	118.2
	16	3.42	0.04 (d)	95.0	94.9	91.9	93.9
	17	5.11	0.98 (s)	43.1	42.2	42.6	42.6
	18	5.87	0.98 (s)	40.8	40.0	39.9	40.2
Fuse sand	12	6.79	0	81.5	81.8	89.2	84.2
	13	6.81	0	82.0	81.3	82.8	82.0
Sipernat	23	1.02	1.02	109.7	109/7	106.9	108.7
	24	1.08	1.04	-	105.5	112.0	108.76
	25	0.58	0.32	211.9	214.5	211.3	212.6
	26	0.41	0 (d)	234.7	238.7	231.2	234.8
	27	1.56	1.30	83.0	84.7	71.1	79.6
	28	2.13	1.83	55.0	56.0	59.6	56.9
	31	2.38	2.62	55.4	56.9	53.3	55.2
	32	0.80	0.62	155.5	151.6	166.3	157.8
Oobleck	29	6.12	0.68	37.2	38.2	47.1	40.8
	30	5.94	0.68	40.8	41.2	47.7	43.2

DISCUSSION

Plotting the M_m/M_c to Peak QSP shows the mitigation effect of the test materials, Figure 5. The plot shows consistency of the materials with a general trend of increasing mass increases the mitigation effect.

The dry vermiculite and perlite show little influence on the QSP with relatively low masses. The dry silica gel crystals and fuse sand have notable effect but stand out from the trend, likely due to their lack of water content, their effects are likely momentum transfer or mechanical in nature.

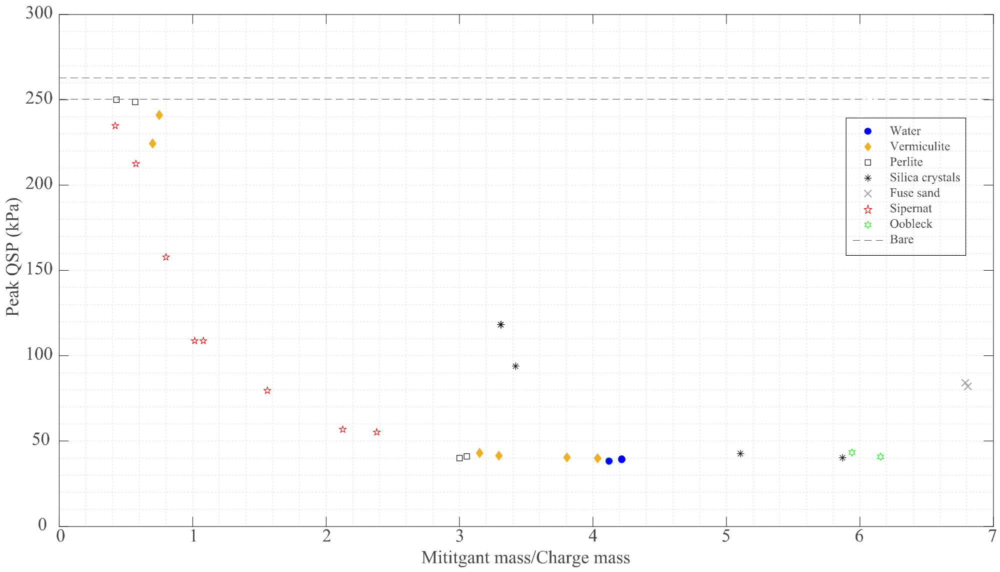

Figure 5: Peak QSP to mitigant mass – charge mass (20g) ratio

The water tests appear as a lower bound with none of the tested materials reducing the QSP further than this floor, in this configuration, despite the presence of samples of greater density. This speaks to the presence of the water as the key mechanism in the mitigation. To investigate the influence of the water component the Peak QSP is plotted against purely the mass of water present in the mitigant materials, Figure 6. The trend observed suggests the presence of the chosen water-bearing materials is insignificant to the effect that the water provides.

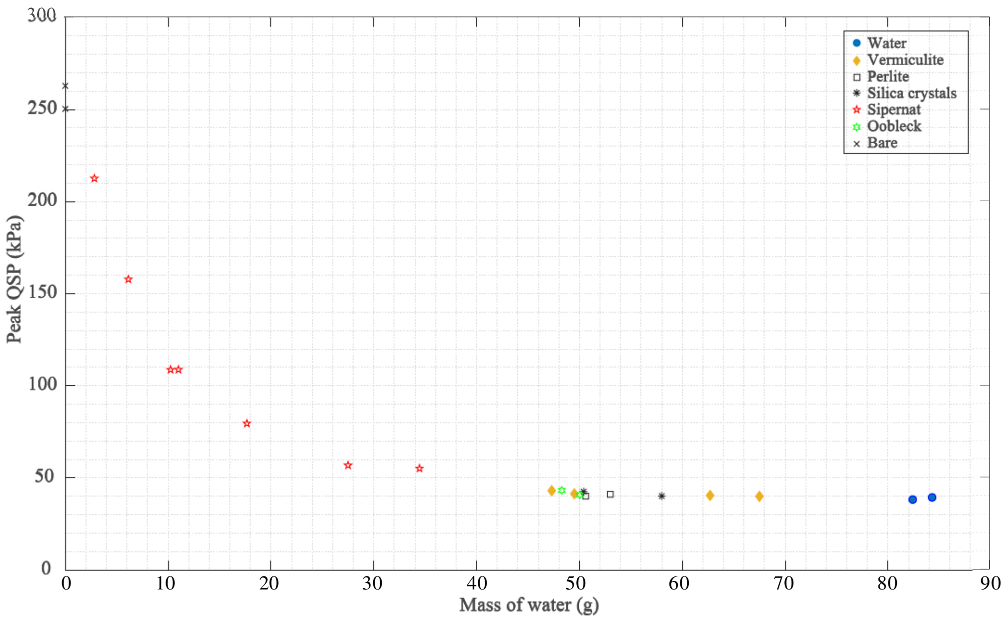

Figure 6: Peak QSP to mass of water, not accounting for solid material mass.

CONCLUSIONS

This paper presents the examination of a preliminary experimental series investigating the mitigation of QSP in confined detonations of PE10 using a range of dry, saturated, and water-bearing materials. The explosive testing has provided a systematic comparison of different material classes and their effects on QSP development against bare charge tests which mitigated cases could be assessed.

The results demonstrate that water, whether employed directly or contained within absorptive carriers, consistently provides the most effective reduction in QSP, lowering values by up to 85%. None of the tested solid materials, even when present at higher densities, surpassed the mitigation floor established by bulk water. Instead, their performance was largely dictated by the quantity of water they could retain. Saturated vermiculite and silica gel achieved QSP reductions comparable to direct water addition, confirming that the primary mechanism of suppression is governed by thermal absorption and phase change of the water content rather than the intrinsic properties of the solid matrix, despite the silica gel having a fair effect dry not being able to add to the effectiveness of water. Conversely, dry vermiculite exhibited only limited or intermediate mitigation, attributable to mechanical energy absorption or momentum transfer rather than significant heat uptake.

These findings reinforce the central role of thermal management and phase change in reducing QSP in confined environments. The dominant factor of maximum QSP reduction is the capacity of the surrounding medium to remove energy from the blast wave and detonation products, principally through vaporisation of water. Materials capable of storing or releasing water in proximity to the detonation represent an effective strategy for deploying mitigation to explosive charges.

The experimental approach, using QSP as the principal diagnostic, has proven to be a practical means of comparing mitigation strategies but has limited capability to identify the mechanisms at play. Further testing to ascertain the momentum transfer component by utilising the special and temporal reflected pressure measurement capabilities of the MaCE rig currently being developed at the University of Sheffield [9], alongside advanced imaging techniques to visualise the material-shock wave interaction to validate models of these energy transfer systems. Future research within the HEADaMM programme will extend these findings by exploring alternative water-bearing matrices, water replacement liquids and the mechanisms that drive them.

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