Enhancing Rock Blasting Efficiency in Mining and Tunneling: A Comparative Study of Shear-Thickening Fluid Stemming and Plug Device Performance

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Abstract: Stemming has a major impact on energy containment inside a blasting hole and is essential for increasing the efficacy of explosive charges in rock blasting. This method is essential in many fields, including road project development, mining, tunneling, and underground construction. By fortifying the confinement of the energy generated by a loaded explosive charge in a blasting hole, stemming increases the fragmentation of rock. Improper or missing stemming leads to the gas escaping in advance from blast holes, resulting not only in the wastage of explosive energy and poor fragmentation but also in environmental problems such as ground vibration, noise, flying rocks, back breaks, and air blasts. When the process to keep gases inside blast holes is not performed correctly or is skipped, it can waste explosive energy and produce poorly fragmented rocks. This also causes problems like high ground vibrations, loud noise, flying rocks, cracks behind the blast area, and strong air shocks. In this study, a shock chamber blasting experiment and numerical analysis were conducted to evaluate the pressure confinement effect of stemming material and plug devices in a blast hole. The resulting stemming effect was compared with that of a shear-thickening fluid (STF)-based stemming material currently under development and sand, which is a commonly used blast stemming material. To evaluate the enhancement of the confinement effect inside the pressurized blast hole, three types of stemming plugs were adopted. The blasting experiment and numerical simulation results revealed that the STF-based stemming materials were superior to conventional stemming materials. In addition, the STF-based stemming and plug system can prevent detonation gas from prematurely overflowing the borehole and effectively prolong the action time and scope of the detonation gas in the borehole.

Keywords: blasting experiment; numerical analysis; stemming effect; shear-thickening fluid; plug system

1. Introduction

Stemming increases rock fragmentation by enhancing the confinement of the gas pressure generated by an explosive charge loaded in a blast hole. It also minimizes vibration and noise by reducing the amount of explosives used. Snelling and Hall [1] published findings from a series of tests using a Trauzl lead block, in which several types of explosives were detonated in both unconfined and confined states with various stemming materials. It was discovered that even the least efficient stemming materials could enhance the blast usable energy by 60%, and the most effective ones might increase it by up to 93%.
Konya and Konya [2] demonstrated that correct stemming increases the explosive efficiency by more than 41%.

Stemming provides the confinement of explosive energy for a longer duration than in a blast hole without it. The most important function of stemming is to maintain the explosive energy within a blast hole and reduce the energy loss from the borehole. Without stemming, up to 50% of the explosive energy can escape through the borehole [3]. Missing or improper stemming, which leads to detonation gas escaping from blast holes in advance, results not only in the wastage of explosive energy and poor fragmentation but also in environmental problems such as ground vibration, noise, flying rocks, back breaks, and air blasts [4].

Previous studies have demonstrated that stemming can lengthen the action time of detonation gases inside blast holes and accelerate explosives’ full reactions, consequently reducing explosive consumption [5,6]. In two experiments, Zhang [7] used a vented charge (no stemming) in one and a confined charge in the other (with stemming). For the latter, the P-wave before the compression pulse was discovered to be 20% longer, and the tailing tension pulse was 50% greater. Additionally, the tailing pulse duration increased by 30%. Zhang [7] also found that stemming improved the maximum crack radius at crack arrest by a factor of five compared with an unstemmed charge.

Stemming, which maintains gas pressure over time, is used to enhance a blast’s performance. Excellent stemming can effectively extend the action period and the range of the detonation gas in the borehole by preventing premature overflow of the borehole with the detonation gas. Additionally, a sizable portion of the rock mass develops cracks. The block size and distribution after blasting satisfy the construction requirements because these fissures spread throughout the rock mass, connect with one another, and cut the rock. Therefore, boosting the blasting impact, increasing explosive efficiency, and attaining optimal blasting fragmentation all depend on an understanding of how to determine stemming reasonably.

The stemming material and length are the two key components of the borehole’s stemming structure. The former is a key factor affecting stemming quality. Using coarse angular material for stemming, compared to fine-powdered drill cuttings, offers increased resistance to premature ejection of blast hole pressure due to its interlocking properties [8]. Choudhary and Arora [9] found that the use of aggregates (10–12 mm in size) and screened drill cuttings (3–7 mm in size) as stemming materials reduced the fragmentation sizes in the collar region compared to drill cuttings.

In general, satisfactory blasting results are obtained when a fluid is used as a stemming material inside a blast hole. Fluid has a higher density than air, and even at extremely high pressures, the compression of water is significantly smaller than that of air [10]. Zhu et al. [11] performed an AUTODYN numerical analysis with various stemming materials, including fluid (water), sand, and air, filled inside the space between the internal explosives and the hollow wall inside the blast hole under dynamic loading (e.g., explosions).

Commonly, fluid (water) expands under the overpressure of air, and this energy is transferred to the rock mass, causing failure and cracks. Thereafter, a high-pressure gas is released through the cracks, contributing to crack extension [12]. In addition, previous studies have analyzed the disturbance effects of water-coupled blasting and quantified the differences in disturbance effects with different coupling media. Authors in [13] demonstrated that crack occurrence was 1.32 times higher when water was used as a medium compared to that when using an air medium [13].

When selecting stemming materials at the blasting site, the confinement performance in the borehole must be considered to obtain an adequate blasting effect with only the planned amount of charge; the adhesion or frictional resistance that can fully resist the ejection of explosive gas must also be considered. After the explosion shock wave is applied to the borehole wall, the fractures in the rock gradually expand owing to the high pressure and explosive gas inside the borehole due to confinement by the stemming part.
Stemming materials with high frictional resistance and good blockage can increase the blasting efficiency by further extending the effective time for the explosive gas to act in the borehole wall. The frictional resistance and blockage performance of the stemming material can be evaluated using the initial ejection velocity of the stemming part at the orifice of the blast hole [14].

In this study, a new stemming material was developed. This material consists of shear-thickening fluid (STF) as a main base, which has a high viscosity for dynamic load and behaves similar to water in shockwave propagation. The STF is characterized by its reversible energy-absorption behavior under impulse loading. Its remarkable energy-absorption capacity is due to viscous dissipation during shear and compression thickening. To comparatively analyze the blasting effect of the developed STF material and that of generally used sand stemming materials, numerical analysis and blasting experiments were performed.

2. Theoretical Background of Stemming

2.1. Mechanical Model for the Stemming Structure

During the wave phase, the structure undergoes significant compression. The primary aim of this study was to investigate the factors affecting the movement of the stemmed structure at a scale. Equation (1) provides a way to calculate the moment of the stemmed structure using the explosion load.

\[
P_x - P_f - G = M_x V_0, \quad (1)
\]

Here, the weight of the stemming assembly is denoted by \( M_x \) in kilograms, while \( V_0 \) represents the speed at which the stemming component is ejected, in meters per second, towards the entrance of the blast hole. \( P_x \) stands for the explosive force applied, \( P_f \) signifies the resistance experienced between the stemming structure and the inner surfaces of the borehole, \( G \) indicates the gravitational force acting on the assembly, and \( P_l \) represents the pressure. A diagram illustrating how the stemming structure is arranged can be found in Figure 1 [15].

2.2. The Pressure Response of the Stemming Framework

Based on the listed information regarding the primary influencing factors that affect the compaction law of the stemming component, we observed the following findings:

1. The higher the pressure of the blasting load, the longer the duration of the detonating gas, and the stronger the ejecting effect of the explosion load on the stemming component (Figure 2a);
2. The looser the initial stemming structure, the greater the compression length and expansion space of the detonation gas in the borehole, and the more noticeable the detonation gas pressure drop during the compression of the stemming structure by the
blasting shock wave. In Figure 2b, the sliding friction coefficient exhibits a direct reflection of the proportional relationship between the sliding friction resistance and the explosion pressure.

![Image of blasting shock wave](image)

**Figure 2.** Pressure behavior on the stemming component: (a) lose stemming before the explosion and (b) compressed stemming after the explosion.

### 2.3. Shock Wave Propagation Characteristics of Stemming Materials

The impact force on the rock mass during a blast can be split into two components: the shock wave from the explosion and the pressure from the detonation gases. This occurs because the rock mass breaks apart due to both the force of the shock wave and the pressure of the detonation gases. Typically, near where an explosion occurs, the shock wave lasts between 10 to 100 microseconds [16].

Various factors, like how the detonation gases expand cracks forming and connecting and their movements in directions, play a role in determining how long this pressure from detonation gases lasts. Studies suggest that in deep hole bench blasting with a decoupling charge setup, this duration is 10 milliseconds based on both research and field tests [17].

When rocks are blasted, shock waves move through where the explosive material meets the stemming material. Some of this shock wave goes into either stemming or rock (transmitted); some reflects back into the blast hole (reflected) upon hitting rock surfaces [7]. The behavior of these waves at boundaries is influenced by differences in impedance. Equation (2) is used to define a medium’s impedance Z:

$$Z = \rho C_p,$$

In this context, \(\rho\) represents the density of the material (kg/m\(^3\)), and \(C_p\) denotes the velocity of sound (m/s). When a shock wave travels from a material of lower impedance to one of higher impedance, there is an increase in shock pressure, and the reverse occurs when moving from high to low impedance. The impedance values for the shear-thickening fluids (STFs) used in this study, along with those for common stemming materials such as aggregate and sand, are detailed in Table 1.

### Table 1. Impedance properties of the general stemming materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (\rho) (kg/m(^3))</th>
<th>Sound Speed (C_p) (m/s)</th>
<th>Impedance ([\text{kg/(m}^2\text{s)} = \text{Rayl}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
<td>330</td>
<td>330</td>
</tr>
<tr>
<td>Dry sand/gravel</td>
<td>1800</td>
<td>750</td>
<td>(1.35 \times 10^6)</td>
</tr>
<tr>
<td>Water</td>
<td>1000</td>
<td>1480</td>
<td>(1.48 \times 10^6)</td>
</tr>
<tr>
<td>Viscous fluid (glycerin)</td>
<td>1260</td>
<td>1908</td>
<td>(2.50 \times 10^6)</td>
</tr>
<tr>
<td>Shear-thickening fluid</td>
<td>1600</td>
<td>2050</td>
<td>(3.28 \times 10^6)</td>
</tr>
</tbody>
</table>
2.4. Blasting Plug Devices

Cone- or wedge-shaped plug devices are generally used for blasting (Figure 3). Worsey developed the most contributing and effective stemming plugs, which had hollow conical- and wedge-shaped mechanical stemming contrivances made from a yieldable elastic material [18]. The wedge shape of the device resists outward movement and compacts against the stemming material during explosive pressure loading. Skagg developed a cup-shaped contrivance made from a yieldable elastic material to absorb explosive energy during blasting [19]. The length of the cup shape offers more contact area for frictional resistance with the blast hole sidewall during the upward force of the explosive energy. Skagg claimed that the elasticity of the device helps to absorb part of the explosive energy in a resilient manner, thereby increasing the effectiveness of blasting. Shann stated that a stem ball filled with a nonreactive material offers great frictional resistance; the diameter of the spherical body of the plug in that study was slightly smaller than that of the borehole [20]. An initial layer of stemming material was required in this design to avoid direct contact between the explosive heat and the device. It was made of a hollow member instead of a solid ball, as illustrated in Figure 3c. A rigid but deformable ball was located in a blast hole with a curved shape, providing clearance between the opposing wall portions. The stemming material was then placed above the hollow device.

![Figure 3. Schematic of a general plug: (a) cone, (b) cup, and (c) ball types.](image)

3. STF-Based Stemming Material

3.1. Shear-Thickening Fluid

A thick colloidal dispersion of solid nanoparticles in a carrier fluid is called an STF [21]. A power law model governs the reversible phenomena known as shear thickening. Any non-Newtonian fluid can be represented in general by the power law model given by Equations (3) and (4) as follows:

\[
\tau = K(\frac{\partial u}{\partial y})^n = K(y)^n = \tau = K(y)^{n-1}(y)^1, \tau \mu_{\text{apparent}}(y),
\]

\[
\mu_{\text{apparent}} = K(y)^{n-1},
\]

In this section, the relationship between shear stress (\(\tau\)) and the factors influencing it in a fluid is explored. Specifically, \(\tau\) is influenced by the viscosity (\(K\)) of the fluid, the shear deformation (\(\mu\)), the distance (\(y\)) from a reference layer, the rate of strain (\(\frac{\partial u}{\partial y}\)), the flow behavior index (\(n\)), and the apparent viscosity (\(\mu_{\text{apparent}}\)).

Delving into the connection between shear stress (\(\tau\)) and the various factors that impact it within a fluid, we find \(\tau\) is affected by the fluid’s viscosity (\(K\)), deformation (\(\mu\)),
distance from a reference layer \((y)\), rate of strain \((\partial \mu / \partial y)\), flow behavior index \((n)\), and apparent viscosity \(\mu_{\text{apparent}}\). Figure 4 illustrates how fluids behave under stress; they exhibit shear-thinning properties when \(0 < n < 1\), demonstrating Newtonian fluid characteristics at \(n = 1\). It is worth noting that dispersions and liquid polymers typically show shear-thinning tendencies within the range of 0.3 to 0.7 for the flow behavior index \((n)\) depending on factors like the weight of the carrier fluid and particle concentration. Additionally, Figure 4 showcases the phenomenon of shear thickening observed in shear-thickening fluids (STFs) characterized by an increase in the rate of shear strain and a rise in shear stress in low-shear–strain-rate regions. Extensive studies have examined STFs for their potential to enhance body armor effectiveness against stabbing assaults \([22,23]\). Further research is needed to assess how effective STFs are when used for blast hole stemming. This study aims to make use of the characteristics of STFs in a versatile stemming method to improve the distribution of pressure waves in the rock mass during explosions. The rheological properties of the Newtonian fluid can be evaluated using a rheometer.

3.2. Rheology Tests for STF-Based Stemming Materials

STF samples were placed between a cone plate and the foundation support of the rheometer for testing using an Austrian rheometer, Anton Paar MCR301. The shear rate of the sample was gradually increased from 0 to 100 s\(^{-1}\) during the experiments conducted at 25 °C. Figure 5a,b display the schematic of the rheometer and the results of the tests on STF-based materials, respectively. The trials revealed a shear-thickening effect at a shear rate of 85 s\(^{-1}\). As the shear rate increased, initially, there was shear thinning in the STF, which later intensified. Notably, as the shear rate attained a critical value, the viscosity of the STF abruptly increased, indicating a shear-thickening phenomenon. However, after some time of experiencing thickening behavior, there was a drop in viscosity. The maximum viscosity observed for the STF sample was 525 Pa, with a shear rate of 85 s\(^{-1}\).
Sand is the most commonly used material for stemming in blasting operations. In this study, the stemming material used for the blasting experiment was common sand with an average particle diameter of 0.52 mm, as shown in Figure 6a, and the STF-based stemming is illustrated in Figure 6b. The particle size sieving curve and properties of the sand used in the experiment and analysis are listed in Table 2.
Table 2. Properties of sand stemming materials.

<table>
<thead>
<tr>
<th>Type</th>
<th>D30 (mm)</th>
<th>D60 (mm)</th>
<th>D50 (mm)</th>
<th>Uniformity Coeff. (Cu)</th>
<th>Coeff. of Gradation (Cc)</th>
<th>Specific Gravity (Gs)</th>
<th>Unified Soil Classification System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.52</td>
<td>0.7</td>
<td>0.62</td>
<td>1.35</td>
<td>1.14</td>
<td>2.65</td>
<td>Sand with poor grade (SP)</td>
</tr>
</tbody>
</table>

When a hammer struck the surface of a mixture called shear-thickening fluid (STF) made up of starch particles ranging from 5 to 20 µm suspended in water, it behaved as if it was a solid surface. To maintain the shear-thickening property and keep the solution workable, an STF blend with a 55% weight concentration was prepared using both ultrasonic agitation methods, described in reference [26]. Experiments with maize starch concentrations between 52.5% and 55% showed that objects bouncing off the suspension’s surface reacted similarly to hitting an object, as explained in reference [27].

Furthermore, the studies referenced in [28,29] found a link between shock wave velocity and STF behavior by utilizing laser-induced shock tests to draw their conclusions.

To illustrate the application of the Hugoniot power series, one can calculate the power series expansion for the linear relationship between shock wave speed ($u_0$) and particle velocity ($u_p$), within the context of STFs.

The basic equations that describe how STFs behave during shock situations, including the principles of mass and momentum conservation as the specified linear relationship between velocities ($u_0 - u_p$), are detailed in Equations (5)–(7) accordingly.

\[ \rho_0 u_0 = \rho (u_0 - u_p), \]  
\[ P_H = \rho u_0 u_p, \]  
\[ U_S = C_0 + Su_p, \]

where $u_0$ is the shock speed, $P_H$ is the Hugoniot curve pressure, $\rho_0$ is the density, $S$ is the linear coefficient, $u_p$ is the particle velocity, and the starting-state velocity of sound is represented by $C_0$.

Table 3 is a list of the STF’s relevant constitutive parameters. It is noteworthy that the creation and collapse of cavitation bubbles in fluids are not described by the Mie–Grüneisen equation of state (EOS). Cavitation, however, is difficult to achieve in fluids with exceptionally high viscosities, such as the STF utilized in this investigation.

<table>
<thead>
<tr>
<th>Type</th>
<th>$\rho_0$ (kg/m$^3$)</th>
<th>$C_0$ (m/s)</th>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>STF</td>
<td>1600</td>
<td>2050</td>
<td>5.324</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sand (dry)</td>
<td>1450</td>
<td>1019</td>
<td>1.325</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

4. Blasting Experiment

4.1. Shock Chamber Model

Controlling the gas pressure within the hole is essential for a blasting operation because it influences how the rock breaks apart during blasting. To investigate the resistance of the material being used, a shock chamber system was set up for an experiment using the dynamic expansion behavior of Nonex Rock Cracker (NRC), which generates gas at a rate of least 300 L per kilogram.

The shock chamber, constructed as a cylinder with a diameter of 125 mm and a height of 500 mm, contained a blasting hole with dimensions of 24 mm in diameter and 450 mm in height. To measure the resistance time of stemming materials’ NRC explosion, a
ventilation hole was drilled in the chamber, and high-speed camera recordings taken at 1200 frames per second were used to determine detonation time based on light emission.

The strength of stemming materials was assessed by adding a thread for gas pressure sensing and monitoring the NRC reaction gas pressure behavior inside the blasting hole. Refer to Figure 7 for an illustration of the shock chamber setup.

![Figure 7. Schematic of the shock chamber system.](image)

4.2. Experimental Design

In this study, our goal was to compare the resistance properties of types of stemming materials. The experiment involved two phases; the main stemming materials included only sand, only STF, STF + spike plug, and STF + twist plug, each measuring 18 cm in length. To simulate an explosion using sand or rock powder on the section of the stemming material when utilizing an STF-based stemming material, we added 17 cm of sand stemming on top to create a stemming length of 35 cm for experimentation. We assessed the velocity and momentum at which the gas pressure decreased due to ejection resistance and binding force of the stem ejected. The configuration of each stemming material used in the trials is detailed in Figure 8.
Figure 8. Schematic of the shock chamber system. Shapes of the stemming materials used in the experiment. (a) Sand, (b) STF, (c) STF + spike plug + sand, and (d) STF + twist plug + sand.

The stemming material was ejected with the gas pressure generated by the NRC explosion to compare the resistance characteristics of the stemming materials. The continuous pressure behavior and ejection speed of the NRC reaction gas were measured to evaluate the resistance of the stemming materials. A piezoelectric (PE) sensor suitable for dynamic pressure measurement was used to measure the behavior of the residual gas pressure in the shock chamber. To collect the data, Mrel’s MicroTrap was used to receive the trigger signal by breaking the circuit of the inserted trigger line such that the instrumentation would start simultaneously with the initiator’s detonation. Additionally, the signal transmitted to MicroTrap was triggered to receive the trigger time required to analyze the ejection rate using a USA manufactured high-speed camera (Phantom M110) capable of shooting 5000 fps, and the gas pressure behavior was measured at 1 μs intervals.

The secondary stemming material’s ejection time was determined by the gas pressure due to NRC (0.15 m), and this information was used to examine the stemming ejection rate. Figure 9 shows the schematic of the shock chamber measurement system for analyzing the ejection resistance of the stemming.
Figure 9. Shock chamber measurement system schematic. (a) Experimental measurement schematic and (b) shock chamber measurement system image.

4.3. Experimental Results

To assess how stemming materials withstand ejection, we investigated at how much pressure remained in the shock chamber after detonating the NRC with each material and examined the ejection rates. The goal of this examination was to determine how much energy is lost due to resisting gas expansion pressure.

4.3.1. Residual Gas Pressure Behavior Analysis

Table 4 shows the outcomes of analyzing how the residual gas pressure behaves in the shock chamber. A PE sensor was utilized to evaluate how well the stemming materials controlled the pressure from blasting gas. This evaluation was based on when the peak pressure occurred in the shock chamber or when the gas pressure returned to its level.

Table 4. Results of the residual gas pressure behavior analysis using voltage data.

<table>
<thead>
<tr>
<th></th>
<th>Peak Voltage (V)</th>
<th>Time of Return to Atmospheric Pressure (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only Sand</td>
<td>2.531</td>
<td>4.425</td>
</tr>
<tr>
<td>STF + Sand</td>
<td>3.172</td>
<td>4.921</td>
</tr>
<tr>
<td>STF + Spike plug + Sand</td>
<td>3.162</td>
<td>4.781</td>
</tr>
<tr>
<td>STF + Twist Plug + Sand</td>
<td>3.529</td>
<td>5.044</td>
</tr>
</tbody>
</table>

The performance of the restraint was then assessed. The study showed that the configuration using “Sand” reached a voltage of 2.531 V, while the “STF + Sand” setup achieved a peak voltage of 3.172 V. There was no difference in peak voltage (3.162 V) between the spike plug case and the STF and sand stemming scenarios. However, the configuration with “STF + Twist Plug + Sand” displayed peak voltage at 3.529 V. The waveforms captured by the measuring tools for all test scenarios can be seen in Figure 10.
Figure 10. Waveform of the measured residual gas behavior.

After the NRC explosion, the highest voltage recorded and how long the gas lingers in the blasting hole demonstrate how well the stemming material resists being pushed out by pressure. A higher peak voltage indicates an impact that creates cracks in the rock when the shockwave from detonation spreads, showing that the stemming material can contain the impact within the blasting hole. Additionally, the time it takes for gas pressure to settle to zero in the blasting hole indicates how long the gas pressure is sustained. The longer the gas pressure remains in the blasting hole, the better the blasting efficiency is believed to be. Hence, if it takes time for the pressure to drop back to zero, it means the gas stays longer in the blasting hole, which signifies blasting efficiency.

In an experiment testing stemming materials, it was found that the “STF + Twist Plug + Sand” combination prolonged both the gas duration and high gas-pressure levels compared to stems used in this study.

4.3.2. Ejection Rate Analysis of the Stemming Material

The study assessed how well each material resisted being ejected using a high-speed camera that took images every 0.82 milliseconds. The time it took for the stem to be ejected was measured from when the detonation began and was observed through the ventilation hole. The results indicated that the ejection velocity decreased in the following sequence: “Only Sand”, “STF”, “STF + Spike Plug + Sand”, and “STF + Twist Plug + Sand”. Figure 11 displays the images captured by the camera, which recorded 1200 frames per second for analysis purposes.

Based on the observed ejection resistance tendencies of stemming materials with a 1200 fps camera, a 5000 fps high-speed camera was utilized to calculate the ejection speed and momentum of the secondary stem ejected by the gas pressure. For the momentum calculations, the mass of the stemming component was set at 150 g. The analysis results from the 5000 fps high-speed camera are presented in Table 5, and Figure 12 displays the high-speed camera images used for the analysis.
Figure 11. Images from the 1200 fps high-speed camera used for the analysis. (a) Sand, (b) STF, (c) STF + spike plug + sand, and (d) STF + twist plug + sand.

Table 5. Results of the stemming material ejection rate analysis.

<table>
<thead>
<tr>
<th>Stemming Material</th>
<th>Resistance Time (ms)</th>
<th>Terminal Ejecting Velocity (m/s)</th>
<th>Momentum (N·s)</th>
<th>Relative Blockage Performance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only Sand</td>
<td>3.0</td>
<td>100</td>
<td>13.5</td>
<td>100.0</td>
</tr>
<tr>
<td>STF + Sand</td>
<td>3.2</td>
<td>93</td>
<td>12.5</td>
<td>107.5</td>
</tr>
<tr>
<td>STF + Spike Plug + Sand</td>
<td>3.6</td>
<td>83</td>
<td>11.2</td>
<td>120.4</td>
</tr>
<tr>
<td>STF + Twist Plug + Sand</td>
<td>3.8</td>
<td>77</td>
<td>10.5</td>
<td>130.0</td>
</tr>
</tbody>
</table>

The time it took for the stemming to resist action was noted as 3, 3.3, 3.5, and 3.8 milliseconds for the scenarios involving “Sand”, “STF + Spike Plug + Sand”, and “STF + Twist Plug + Sand”, respectively. By calculating the momentum loss towards the shock chamber entrance, based on these resistance times, it was found that using “STF + Sand” resulted in a 7.5% enhancement in blockage performance compared to scenarios with sand as the stemming material. A lower momentum value indicates a better resistance performance of the stemming material.

Moreover, an improvement in blockage performance was observed with the use of STF stemming material along with a plug device. Specifically, employing a plug led to a blockage enhancement of around 1.28 times compared to using sand for stemming.
<table>
<thead>
<tr>
<th></th>
<th>Detonation Time</th>
<th>Reference Distance Reaching Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>0 ms</td>
<td>3.0 ms</td>
</tr>
<tr>
<td>(b)</td>
<td>0 ms</td>
<td>3.2 ms</td>
</tr>
<tr>
<td>(c)</td>
<td>0 ms</td>
<td>3.6 ms</td>
</tr>
<tr>
<td>(d)</td>
<td>0 ms</td>
<td>3.8 ms</td>
</tr>
</tbody>
</table>

**Figure 12.** Images from the 5000 fps high-speed camera used for the analysis. (a) Sand, (b) STF, (c) STF + spike plug + sand, and (d) STF + twist plug + sand.
Finally, the histograms shown in Figure 13 illustrate ejection velocity, momentum per unit mass of stemming material, and relative blockage performance analyzed based on ejection time for each scenario involving stemming materials.

![Figure 13](image)

Figure 13. Images from the 5000 fps high-speed camera used for the analysis. Red: Only sand, green: STF + sand, dark blue: STF + spike plug + sand, and light blue: STF + twist plug + sand.

The speed at which the stemming material is pushed out of the blasting hole decreased as the gas pressure resistance of the material increased. Among types of stemming materials tested, “STF + Twist Plug + Sand” showed an ejection rate that was 0.8 ms slower than the regular sand stem. Its resistance performance improved by 30% in terms of momentum. The analysis revealed that all stemming materials exhibited the following order of ejection resistance: “Sand”, “STF + Sand”, “STF + Spike Plug + Sand”, and “STF + Twist Plug + Sand”.

A high speed of ejecting secondary stemming material indicates a loss in blasting pressure towards the inlet of the blasting hole due to pressure being reduced by the stemming material’s binding ability.

Based on measurements, the duration that the secondary stemming material resists blast pressure and its momentum at the hole entrance suggest how the primary stemming material withstands blast pressure before being ejected due to reduced pressure. This suggests that pressure lingers in the blast hole longer, aiding crack propagation.

Therefore, we demonstrated that the better the pressure-binding ability of the primary stemming material, the longer the resistance time.

5. Numerical Simulation

5.1. Material Properties of the Stemming Material

A computerized simulation was conducted using ANSYS AUTODYN to mimic the blasting test in the shock chamber following the use of STF-based and sand stemming. The air properties were calculated using the ideal gas equation of state (EOS), while the materials listed in Table 3 were analyzed using impact-state equations. Different constitutive equations were utilized depending on the state to study variations in volume and shape under external forces using the EOS.

5.2. Shock Chamber Model

The numerical model utilized a mix of Eulerian and Lagrangian methods. The explosives’ stemming material and air were represented in the mesh, while the steel cylinder was depicted in the Lagrange mesh. The combined Eulerian algorithm enabled interaction between the blasting shock wave and the shock chamber. The Lagrangian element representing the shock chamber was linked within the part (air) to maintain an explosive gas flow a ratio of 4:1 between the Lagrangian and Eulerian grids. Additionally a friction
coefficient of 0.6 was set between the sand stemming material near the orifice and the shock chamber wall in the blast hole.

In this research, explicit hydrodynamic simulation tools like AUTODYN played a role with the use of a coupled Euler–Lagrange approach. This method leverages the ability of an interface to intersect with a fixed Eulerian grid in any direction. The interactions between Eulerian cells and the Lagrangian interface assist in establishing a pressure distribution along the boundaries of elements, as shown in Figure 14. The design of the shock chamber model involved creating a three 3D structure within a Lagrangian framework comprising 80,000 elements, as detailed in Figure 15.

In studying the materials inside the blast hole, such as the explosive substances, we used the method with 360,000 elements. Additionally, the 3D analysis used a mix of Euler–Lagrange techniques. This method involved using a mesh resolution of 2 mm by 2 mm by 10 mm for elements representing the conditions around the explosion area.

![Figure 14. Schematic of the coupling Lagrangian–Eulerian meshes.](image)

![Figure 15. AUTODYN numerical model of the shock chamber model.](image)

The Jones–Wilkins–Lee model was used, and trinitrotoluene (TNT) was set as the explosive charge (Table 6). TNT properties were provided in the AUTOUDYN program. For the air conditioning, the internal energy was input as $2.068 \times 10^5$ J/kg, corresponding to the standard atmospheric conditions.

Table 6. Chapman–Jouguet (C-J) and Jones–Wilkins–Lee (JWL) characteristic values (TNT).

<table>
<thead>
<tr>
<th></th>
<th>A (GPa)</th>
<th>B (GPa)</th>
<th>R1</th>
<th>R2</th>
<th>w</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>371.2</td>
<td>3.231</td>
<td>4.15</td>
<td>0.95</td>
<td>0.3</td>
</tr>
</tbody>
</table>

An outflow condition was established around the air region to allow gas to escape, and a boundary condition was set at the edges of the model, surrounding the shock chamber.

To prevent deformation of the shock chamber, a low-power, non-explosive chemical expansion agent called NRC was utilized. In this model, Equation (8) introduced the TNT equivalent, which was then applied to the model. Taking into account NRC’s heat of
combustion at 3452 kcal/kg and an explosion yield factor of 0.2, it was determined that 30 g of NRC is equivalent to 18 g of TNT. In this context, $W$ signifies the TNT equivalent in kilograms, $\mu$ denotes the explosion yield factor, $M$ represents the mass of the explosive in kilograms, and $E_c$ stands for the heat of combustion of the explosive in kcal/kg.

$$W = \frac{\mu \times M \times E_c}{1140}$$

(8)

5.3. Simulation Cases and the Plug Device

Figure 16 shows the model used to study how sand and STF stemming impact outcomes. Explosives were positioned on the left side, while either sand stemming or a mixture of STF and sand stemming was placed on the right side. The choice to combine STF with sand was based on research findings. Chiappetta noted that using crushed rock and a softer, loose material can reduce stemming ejection and improve gas containment [31].

Figure 16. Comparison of the AUTODYN stemming effect between the sand and STF. (a) Only sand stemming and (b) STF and sand stemming.

Figure 17a illustrates the design of the stem model featuring a combination of a cone-shaped plug device and STF sand, while Figure 17b,c display the analysis models for the plug devices introduced in this research. The crafted plug device along with the shear-thickening fluid was created to twist and block the blasting hole upon exposure to detonation gas, consequently boosting friction. Furthermore, the interior of the plug device was filled with stemming material based on STF, which was anticipated to improve its stemming effectiveness.
5.4. Analysis Results for Each Stemming Model

In the analysis of the shock chamber model, we focused on two stemming methods: sand and “STF + sand” stemming. We also looked at three types of stem plug devices used with STF. Following the explosion, the initial ejection of the stemming area began at 0.2 ms for sand and 0.3 ms for STF, with the STF initial ejection velocity being slower at 73% compared to sand stemming. The use of plug devices caused a delay in the time of ejection for the stemming part when compared to the “STF + Sand” model without a plug.

For spike- and cone-type stemming materials, the initial ejection time was observed to be 0.32 ms after the explosives initiation, which was a delay of 0.02 ms compared to combined STF and sand stemming models without a plug device. In cases where twist plugs were used in combination with STF, the start time of stemming part ejection was measured at 0.36 ms post detonation, indicating better resistance performance compared to analyzed scenarios. To track pressure changes over time, a pressure gauge was placed on one side of the shock chamber cylinder, corresponding to half of all stemming components. The maximum pressures recorded at this location are listed in Table 7.

### Table 7. Numerical analysis results of each stemming model.

<table>
<thead>
<tr>
<th>Stemming Material</th>
<th>Initial Ejecting Time (ms)</th>
<th>Initial Ejecting Velocity (m/s)</th>
<th>Peak Pressure (MPa)</th>
<th>Momentum (N·s)</th>
<th>Relative Blockage Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only Sand</td>
<td>0.20</td>
<td>450</td>
<td>300</td>
<td>60.6</td>
<td>1.00</td>
</tr>
<tr>
<td>STF + Sand</td>
<td>0.30</td>
<td>330</td>
<td>350</td>
<td>44.6</td>
<td>1.35</td>
</tr>
<tr>
<td>STF + Cone Plug + Sand</td>
<td>0.32</td>
<td>380</td>
<td>351</td>
<td>37.8</td>
<td>1.60</td>
</tr>
<tr>
<td>STF + Spike Plug + Sand</td>
<td>0.32</td>
<td>260</td>
<td>353</td>
<td>35.1</td>
<td>1.72</td>
</tr>
<tr>
<td>STF + Twist Plug + Sand</td>
<td>0.36</td>
<td>220</td>
<td>395</td>
<td>29.7</td>
<td>2.04</td>
</tr>
</tbody>
</table>

At 0.1 milliseconds after the explosion, the pressure peaked at the location, showing a 15% increase when using STF stemming material instead of just sand. The twist-type plug device recorded a pressure of 395 MPa.

The shock wave from the blast initially compacted the stemming structure, pushing it towards the opening until all stemming structures were ejected during the blasting process. In blasting procedures, a common method is to use a stemming ejection model at the...
opening, determining the velocity of stemming material based on momentum and energy-conservation principles. The effectiveness of stemming was evaluated by calculating momentum for each case and comparing it to a baseline momentum value of 60.6 N·s in a sand stemming setup. A value above 1.0 signifies good performance in stemming blockage.

Figure 18 analyzes the ejection velocity over time at the tip of the sand stemming component inside the blasting hole.

![Figure 18](image.png)

**Figure 18.** Ejection movement of the stemming component with time, showing effectiveness of the stemming material.

The initial ejection speed is the rate at which the outermost material starts coming out of the blast hole. When sand was used as stemming material, it quickly moved out once the material began to be ejected from the hole. However, in cases with STF stemming, the movement of ejection showed an increase. Using a plug device caused a notable decrease in the speed of the stemming material’s ejection. The slope on the velocity time graph indicates how fast the stemming material accelerates when it begins moving. In physics, acceleration is defined as how velocity changes over time for an object. The acceleration direction of the stemming material depends on the gas pressure acting on it.

When STF was used as stemming material, acceleration dropped by around 30% compared to using sand. Introducing a plug device with STF stemmed materials led to a reduction in ejection acceleration.

The use of the plug notably decreased the speed of ejection by 32% when compared to the “STF + sand” stemming method. Figure 19a,b exhibit the pressure patterns for the models using “sand” and “STF + sand” as stemming materials, respectively. Mixing STF with sand improved the stemming effect compared to using sand, resulting in a more intense pressure distribution around the explosive chamber. Additionally, incorporating a plug device further enhanced the impact.

In Figure 19c,d, it was observed that the initial velocities of ejection for materials within the cone, spike, and twist plug models were 280 m/s, 260 m/s, and 220 m/s. The twisted plug demonstrated the highest resistance to explosion pressure among all analyzed models due to its interlocking design. The movement and rotation of its components increased resistance within the blast hole, prolonging its presence compared to configurations, as shown in Figure 19e.
Figure 19. Initial Stemming Ejection Pressure Profiles. This includes (a) sand only, (b) STF + sand, (c) cone + STF + sand, (d) spike + STF + sand, and (e) twist + STF + sand.
Among the analyzed cases, the highest pressure was observed in the shock chamber model that combined the STF stemming material with the twist plug. Compared to using only sand as stemming material, the blockage performance of the blast hole improved by 35% by using STF stemming material. Furthermore, when the plug device was used in conjunction with the STF stemming material, the blockage performance was enhanced by 60–100% compared to the scenarios where only sand stemming was employed.

6. Discussion

After the explosion, in the borehole, a powerful shock wave was unleashed inside the structure compressing it until it reached the opening. The movement of the resulting structure can be divided into two stages: a wave stage influenced by the shock wave and a larger-scale motion stage driven by the detonation gas.

Once the borehole was filled with detonation gas, the stemming structure started to shift due to this gas impact. At the time, the detonation gas aided in expanding existing cracks and creating ones, providing more space for expansion and reducing pressure. Figure 18 shows a graph of time pressure measurements on a cylinder wall representing half of the stemming area in a numerical analysis model. While there were variations among model cases movement, in this analysis, the models’ stemming area began between 0.20 and 0.36 milliseconds after detonation. Using STF as stemming material resulted in enhanced blockage performance compared to using sand (Figure 20a), and incorporating a plug device further intensified the stemming effect (Figure 20b). Using materials or plug devices efficiently extended the duration of blast pressure within the blast hole, leading to an intensity of shock pressure along the blast hole perimeter, producing successful blasting results.

![Figure 20](image-url). Pressure contour at the initial ejection of the stemming time–pressure curve of the numerical model results. (a) Stemming materials only and (b) a stemming material with plug.

The diagram in Figure 21a illustrates the layout of the blast hole with stemming. Once the primer is activated at the base of the blast hole, detonation progresses through the material. This visual representation indicates that the detonation reaches point B. If a high-pressure gauge is positioned at point C within the hole and starts recording from when the primer is ignited, it captures a waveform of either a detonation wave or borehole pressure, as depicted on the side of Figure 21b. In this scenario, the continuous line reflects the borehole pressure corresponding to each stemming technique employed.
Horizontal lines E–F show the durations of detonation from point A to point B. When the shock front reaches point C, the gauge registers a peak shock known as the von Neumann spike, indicating the pressure in the response zone. The brief durations of both the shock wave and pressure in the response zone are depicted by the segment of the pressure curve between points F and G. As the detonation progresses from point C to point D, there are variations in pressure, as illustrated by the curve between points F and G. Assuming a wave velocity for incident or reflected waves within the system, there is a change in pressure at point C from point G to H as the detonation wave travels from B to D and then back to B. Notably, during this phase (G–H), some of the stemming material is expelled from the blast hole.

The reflected wave continues its path towards the bottom of the hole. Interaction between this reflected wave and the original wave within starts at point H on this curve. Furthermore, if cracks have not formed at its bottom yet, there would be another reflection of this reflected wave at that level.

In the graph sections H–I, it is clear that the gases from around point B can escape through the walls and collar of the hole as they move from point H. Once the blast hole is fully opened, the pressure gradually returns to atmospheric levels.

The extrusion resistance performance was analyzed by using twist and plug models. Figure 22 illustrates how the plug area deforms before breaking. Figure 22a shows that when the two parts intersected, they rotated by pressure, and 0.02 ms after detonation (Figure 22b), there was contact between these components, leading to expansion towards the blast hole wall for better stemming effect. After the plug device broke, as shown in Figure 22c, frictional resistance disappeared, allowing the pressure to transfer to the STF stemming layer.

The spike plug model shown in Figure 22d consists of a body with a steel plate shaped like a horseshoe. When pressure is applied to this steel plate tip, compression in direction occurs at a point opposite to its shape, increasing friction with the blast hole wall (Figure 22e). During the analysis, there was no rotational movement noted with the spike plug. The vector component decreased notably towards the blast hole direction once the plug device broke (see Figure 22f). In the case of the twisted plug, it had a larger contact area with the blast hole wall compared to the spike plug. This resulted in an plugging action due to the onset of cross-rotation of the plug.
The way the twist plug functions inside the blast hole can be described as follows: (1) It initially faces resistance until it is entirely displaced by the pressure from the blast. (2) When in contact, the initial component of the twist plug starts to turn against the opposing component. (3) As each piece of the plug rotates, it brings the device into direct contact with the wall of the blast hole, enhancing its ability to block effectively.

7. Conclusions

In this research, an experiment involving blasting was carried out using a shock chamber system, along with analysis to assess how well various combinations of STF-based stemming materials and plug devices performed. The study resulted in the following findings:

1. The blockage performance improved when STF stemming material was mixed with sand, showing a 7.5% enhancement compared to using only sand for stemming;
2. The application of a plug device to the STF stemming model further enhanced the blockage performance in the blast hole. Through blasting experiments and numerical analysis, the twist-type plug designed in this study demonstrated the highest blockage effect and frictional resistance in the blast hole, achieving a blockage performance exceeding by 130% that of common sand stemming;
3. STF-based stemming materials are cost-effective and can be easily utilized at blasting sites. These materials lack internal voids and exhibit superior blockage performance in the blast hole. Their compression resistances are significantly better than those of existing unconsolidated or solidified materials. STFs are incompressible fluids that do not undergo volume changes due to external forces; however, they experience a rapid increase in viscosity upon impact. Generally, for open-pit blasting, STF-based stemming materials can be used either in the form of pre-injected packaged products or directly injected into the blast holes. Employing blast stemming in combination with a plug device can lead to enhanced blasting outcomes;
4. STF-based stemming materials have the potential to minimize environmental impact by reducing noise and vibration from the ground, they improve rock fragmentation, and they require fewer explosives in engineering practice. Flexibility and efficiency are enhanced in a variety of blasting scenarios, especially in open-pit mining and tunneling operations, by the capacity to pre-inject STF-based products or inject them straight into blast holes.

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**References**


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