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# Fractured Lost Circulation Control: Quantitative Design and Experimental Study of Multi-Sized Rigid Bridging Plugging Material

**Wei Wang [1,2], Yuxuan Zheng [3,*], Chengyun Ma [4,*], Jianguo Chen [5], Yi Zhang [1], Tongtong Li [1] and Mingjie Li [6]**

[1] Chinese Academy of Geological Sciences, Beijing 100037, China; wangwei1992916@163.com (W.W.); shidazhangyang@163.com (Y.Z.); litongtong@cags.ac.cn (T.L.)
[2] China University of Petroleum (CUPB), Beijing 102249, China
[3] The Second Institute of Hydrogeology and Engineering Geology, Shandong Provincial Bureau of Geology & Mineral Resources (Lubei Geo-Engineering Exploration Institute of Shandong Province), Dezhou 253072, China
[4] China Mechanical Engineering College, Xi'an Shiyou University, Xi'an 710065, China
[5] Daqing Drilling Engineering Company, No. 2 Drilling Company, Daqing 163000, China; jg3434@126.com
[6] Energy and Machinery College, Dezhou University, Dezhou 253023, China; limingjie8663@gmail.com
* Correspondence: 15963398031@163.com (Y.Z.); mcy0000@163.com (C.M.)

**Abstract:** Fractured lost circulation management is a critical challenge in drilling engineering, and existing methods often rely on empirical designs with limited effectiveness. This laboratory-scale study, utilizing modified PPT equipment and nut shell-based rigid particles in simplified linear fractures, systematically investigated the bridging and sealing effect of compounded multi-sized rigid lost circulation material (LCM) through physical experiments. It clarified the mechanism by which the proportion of multi-sized plugging particles and the total concentration influence the sealing effect after compounding. A set of quantitative compounding relationships for multi-sized rigid LCM was established based on the particle size-to-fracture width ratio (R = D50/w, where D50 is median particle diameter and w is fracture width). Experimental results show that when using particles with specific R (e.g., R = particle size/fracture width) values, approximately R1 = 0.7, R2 = 0.45~0.3, and R3 = 0.08, in a 1:1:1 ratio, and the total concentration is around 4%, high-efficiency plugging can be achieved. The plugging formulation based on this design principle can effectively seal medium-scale lost circulation fractures, providing a theoretical basis for the scientific design of rigid LCM in fractured formations.

**Keywords:** fractured lost circulation; rigid lost circulation material; multi-sized compounding; quantitative design; plugging effect

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Academic Editor: Qingmin Yu

Received: 26 April 2025
Revised: 15 May 2025
Accepted: 26 May 2025
Published: 29 May 2025

**Citation:** Wang, W.; Zheng, Y.; Ma, C.; Chen, J.; Zhang, Y.; Li, T.; Li, M. Fractured Lost Circulation Control: Quantitative Design and Experimental Study of Multi-Sized Rigid Bridging Plugging Material. *Processes* **2025**, *13*, 1701. https://doi.org/10.3390/pr13061701

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## 1. Introduction

Fracture loss has long been a global challenge in the field of drilling engineering, with many key issues remaining unresolved. One of the core reasons lies in the lack of specialized design theories and methods for rigid LCM specifically targeting fracture loss. As a commonly used and indispensable material type in fracture loss control, rigid LCMs primarily function by forming a bridge and dividing the fracture space within the loss fracture, constructing a sealing wall, and converting the fracture into pores. This significantly increases the flow resistance of drilling fluids in the loss channels, reducing the loss of drilling fluids. The reasonable design of the type, concentration, and particle size distribution of rigid LCMs is crucial for improving the first-time success rate of fracture loss control.

Traditional rigid LCM design principles, such as the one-third bridging rule [1], ideal packing theory [2–5], and the Vickers method [6], are primarily based on the assumption that the lost circulation channels are of the pore type. This makes them difficult to effectively apply in fractured lost circulation scenarios. These methods exhibit obvious limitations in fractured lost circulation formations, such as slow bridging speed and insufficient compactness of the sealing layer. Therefore, developing design theories and methods for rigid bridging LCMs applicable to fractured lost circulation is of significant practical importance.

In recent years, domestic and international scholars have proposed a series of design criteria or theories for LCMs specifically targeting fractured lost circulation channels. For example, Whitefill [7] suggests that the optimal sealing effect is achieved when the median particle size D50 of the bridging material equals the fracture width. Razavi O et al. [8] proposed that the particle size distribution curve of the LCM should exhibit a bimodal distribution characteristic. Alsaba M. et al. [9] found through research that the lost circulation control effect is optimized when the bridging particle D50 is greater than 3/10 of the fracture width, and D90 is greater than 5/6 of the fracture width. Kang Yili et al.'s [10] research shows that, under the same particle size range conditions, flake LCMs have a higher probability of retention in fractures than spherical LCMs. Zhao Yang et al. [11] pointed out that the design of the main bridging particle D90 size is extremely critical, and it should be greater than or equal to 0.9 times the fracture width at the bridging point and less than the entrance width. Wenhao He et al. [12] believe that traditional LCM design methods, which are based on the maximum pore throat size, make it difficult to maximize the sealing effect, and they emphasize that D50 should equal the average pore throat size. Wang Gui et al. [13] established a new LCM design method, namely that the ratio of the characteristic particle size of the LCM to the fracture width should be between 0.5 and 0.7, and D10 should be 0.1–0.2 mm, and the relative particle size span Sp = (D90 − D10)/D50 should be $\geq$1.5.

However, most of the aforementioned bridging LCM design methods did not explicitly define the quantitative compounding relationship between the characteristic particle sizes of the LCMs. With increasing drilling depth, the geological environment becomes increasingly complex, and the scales of lost circulation fractures diversify, making the multi-component bridging lost circulation material compounding technology an inevitable choice in drilling operations [14,15]. Currently, the selection of bridging LCMs for complex-scale lost circulation fracture networks still relies on experience and has not fundamentally solved the scientific problems involved in compounding multiple LCMs [16], resulting in the lost circulation problem not being effectively controlled or eliminated. In view of this, this paper, focusing on the basic characteristics of fractured lost circulation and utilizing a modified PPT fractured lost circulation experimental apparatus, conducted indoor bridging lost circulation experimental research, aiming to explore and establish a quantitative compounding method for multi-sized rigid LCMs. Specifically, this study investigated the synergistic bridging and sealing effects of different particle size fractions based on their size-to-fracture width ratio R (R = D50/w), leading to the development of a specific quantitative relationship for a triple-particle system. This approach, grounded in experimental validation and supported by particle packing theory, provides a more scientific and direct basis for the design of rigid bridging LCM formulations for fractured formations, addressing the limitations of current empirical or qualitatively-guided methods. The flowchart of this article is shown in Figure 1.

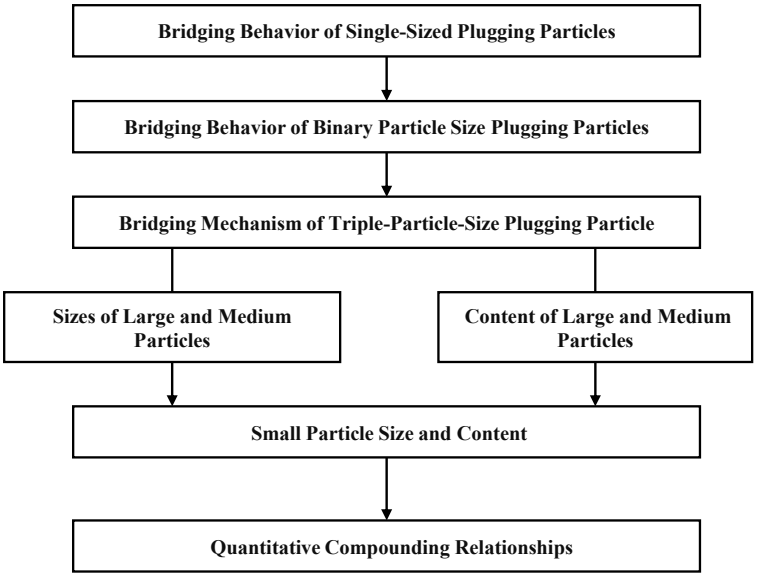



**Figure 1.** Workflow diagram.

## 2. Experimental Apparatus, Materials, and Conditions

The permeability plugging apparatus (PPA) is a commonly used method for leak-off evaluation [17], but conventional PPA testing is primarily used to assess pore plugging or the absence of deep fractures. This does not align with the characteristics of leakage pathways in fractured formations. The apparatus used in this study was modified based on the PPT Permeability Plugging Tester. The improved PPT fractured lost circulation tester primarily included key components such as a lost circulation slurry chamber, a fracture block (see Figure 2), and a hydraulic pump. Specifically, the geometric parameters of the fracture block were a fracture inlet width of 3 mm, an outlet width of 1.5 mm, and a length of 40 mm; the direction of fluid flow was from bottom to top. In the experiment, the selected rigid bridging LCM was nut shells. Due to their high strength, low density, and good environmental compatibility, nut shells have become one of the most widely used bridging LCMs currently [10]. To thoroughly investigate the quantitative compounding relationship of rigid LCMs of various sizes, this study, based on the ratio of rigid bridging lost circulation material size to the fracture inlet width (abbreviated as: particle size-to-fracture width ratio, i.e., R = D50/w, where D50 is the median particle diameter and w is the fracture inlet width), divided the rigid LCMs into 12 grades. The specific grading details are shown in Figure 3. During the experiment, a slow and intermittent injection method was employed to inject the lost circulation slurry into the fracture. The specific operating procedure was as follows: After increasing the pressure by 1 MPa, that pressure was maintained for 5 min until the sealing layer was broken, at which point the experiment was stopped. The maximum pressure bearing capacity of the sealing layer was determined by the pressure value displayed on the pressure gauge just before the sealing layer broke. The criterion for judging the failure of the sealing layer is that during continuous injection, the pressure on the pressure gauge remains constant for a prolonged period. This experimental method can effectively simulate the process of LCMs migrating, accumulating, and sealing within fractures during actual drilling operations, providing scientific and accurate experimental means for studying the performance of LCMs.

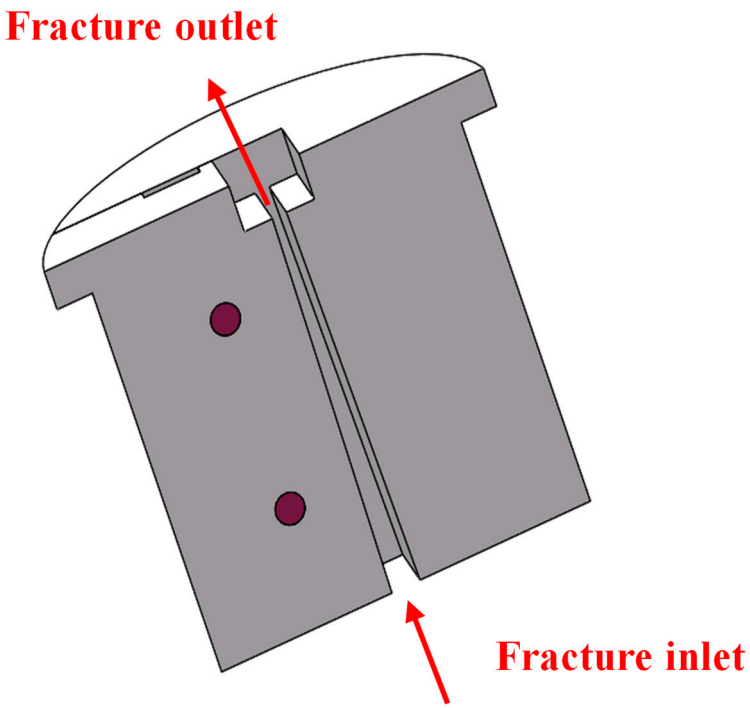



**Figure 2.** Fracture module.




**Figure 3.** Photos of 12 different–sized grades of rigid LCMs.

## 3. Analysis of Experimental Results

### *3.1. Bridging Behavior of Single-Sized Plugging Particles*

In single-sized particle plugging experiments, the test pressure was generally close to zero. This phenomenon reveals the significant limitations of single-sized plugging particles in fracture sealing. Through an in-depth analysis of the bridging behavior of single-sized plugging particles within fractures (see Figure 4), the following regularities can be derived:

- When R > 0.5: Once plugging particles enter the fracture, they can form a stable bridging structure within it. This bridging behavior is primarily governed by the particle size of the plugging material. When the size of the plugging particle is greater than half of the fracture outlet width, significant mechanical interlocking effects occur between the plugging particles and the fracture walls, thus quickly establishing a stable bridging structure. In this case, the size advantage of the plugging particles enables them to complete bridging independently, without the synergistic action of

other particles. Therefore, for larger-sized plugging particles (R > 0.5), their sealing capability within the fracture primarily depends on the degree of matching between the particle size and the fracture width.

- When 0.3 < R < 0.5: Plugging particles within this size range cannot directly form single-particle bridging within the fracture on their own. Only when two or more plugging particles simultaneously reach a certain location within the fracture and interact for a period of time can a stable bridging structure be formed within the fracture. Furthermore, as R decreases, the required number of plugging particles significantly increases. This indicates that within this particle size range, the bridging behavior of plugging particles is not only influenced by particle size but is also constrained by particle concentration. Higher particle concentration is more conducive to the formation of bridging. Therefore, for medium-sized plugging particles (0.3 < R < 0.5), their sealing capability within the fracture does not only depend on particle size but is also closely related to particle concentration.
- When R $\leq$ 0.3: Plugging particles within this size range are almost unable to form a stable support structure within the fracture (see Figure 4, R = 0.3). Unless an extremely high plugging particle concentration is used, effective bridging is difficult to achieve. However, using such high concentrations is unrealistic in actual field operations. Therefore, plugging particles within this size range cannot serve as fracture bridging particles and can only be used as filling materials. This indicates that for smaller-sized plugging particles (R $\leq$ 0.3), their sealing capability within the fracture is extremely limited, making it difficult to meet actual engineering requirements.

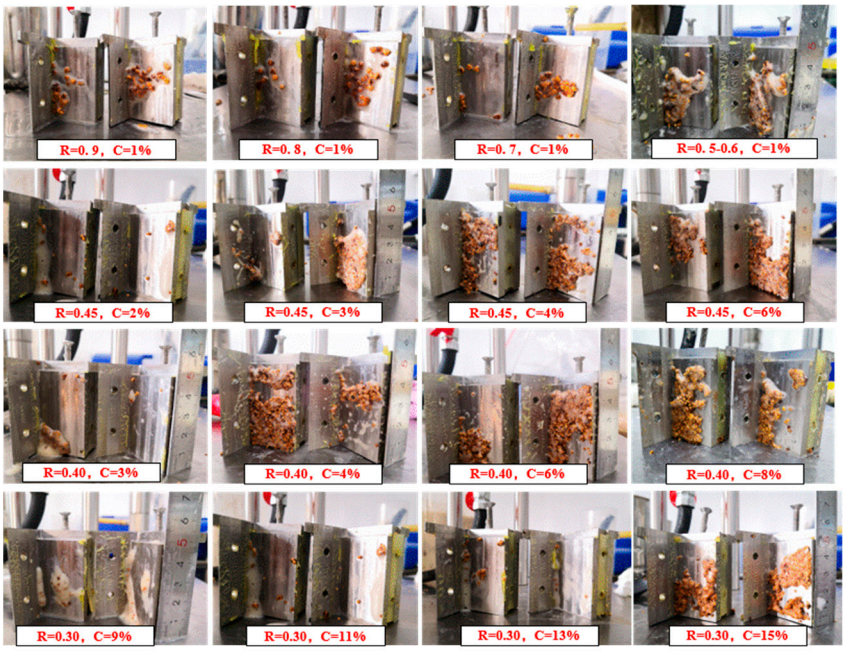



**Figure 4.** Bridging results of single–sized plugging particles within the fracture. (Note: In the figure, R represents the ratio of particle diameter to fracture width, i.e., R = D50/w; C represents particle concentration).

In summary, although a certain degree of bridging can be achieved within the fracture merely by changing the particle size or concentration of single-sized plugging particles, a dense sealing layer cannot be formed. In other words, in the actual application in fractured lost circulation formations, single-sized plugging materials have obvious limitations. This finding provides important insights for subsequent research, namely that when designing plugging materials, consideration should be given to using multi-sized combinations or

other composite material systems in order to improve the plugging effect and meet actual engineering requirements.

### 3.2. Bridging Behavior of Binary Particle Size Plugging Particles

Based on the experimental results of single-sized plugging particles, this study classified the nut shell plugging particles into three grades: large, medium, and small, according to the particle size-to-fracture width ratio (abbreviated as particle size-to-fracture width ratio, i.e., R = D50/w). The specific classification is as follows:

- Large particles: Refer to plugging particles with a particle size-to-fracture width ratio of $R > 0.5$. These particles, by virtue of their size advantage, can establish stable bridging structures within the fracture, achieving effective sealing of the fracture.
- Medium particles: Refer to plugging particles with a particle size-to-fracture width ratio of $0.3 \leq R \leq 0.5$. Particles within this size range cannot form bridges within the fracture individually; they require the synergistic action of two or more particles accumulating and interacting with each other to form a stable bridging structure within the fracture. This combination exhibits higher bridging and plugging efficiency compared to other binary mixes tested, though it still requires a higher total concentration compared to the optimal triple-particle system to achieve minimal loss. For example, the combination of 3% (R = 0.45) medium particles and 2% (R = 0.08) small particles resulted in a total lost volume significantly lower than other binary mixes shown in Figure 4. This is because the medium-sized particles (R = 0.45) can initiate some multi-particle bridging structures within the fracture, and the smaller particles (R = 0.08) can then effectively fill the significant voids remaining within this preliminary structure, enhancing the sealing effect and reducing fluid loss through a synergistic filling mechanism.
- Small particles: Refer to plugging particles with a particle size-to-fracture width ratio of $R < 0.3$. Due to their small size, they cannot form effective mechanical support within the fracture and find it difficult to establish bridging structures independently. They can only be used as filling materials to fill the pores between larger particles and enhance the sealing effect.

Figure 5 shows the impact of binary particle size combinations of plugging particles on the total fluid loss. The analysis results indicate the following:

- Combination of Medium and Small particles: This combination exhibits higher bridging and plugging efficiency but also requires a higher concentration of plugging material. After medium particles form the initial bridging structure within the fracture, small particles can fill the pores between the medium particles, enhancing the sealing effect. However, since small particles cannot bridge independently, sufficient concentration is needed to effectively fill the pores and form a denser sealing layer.
- Combination of Large and Small particles: Although large particles can form bridges within the fracture, the size of the pores created by their bridging is much larger than the size of the small particles, making it difficult for small particles to remain within the fracture and effectively fill the pores. Therefore, although this combination can form bridges within the fracture, it cannot establish a dense sealing layer, and the overall sealing effect is limited.
- Combination of Large and Medium particles: Although large and medium particles form bridges within the fracture, without the filling by small particles, the formed sealing layer has large pore sizes. Thus, although this combination can form bridges within the fracture, it also cannot establish a dense sealing layer, and the overall sealing effect is limited.

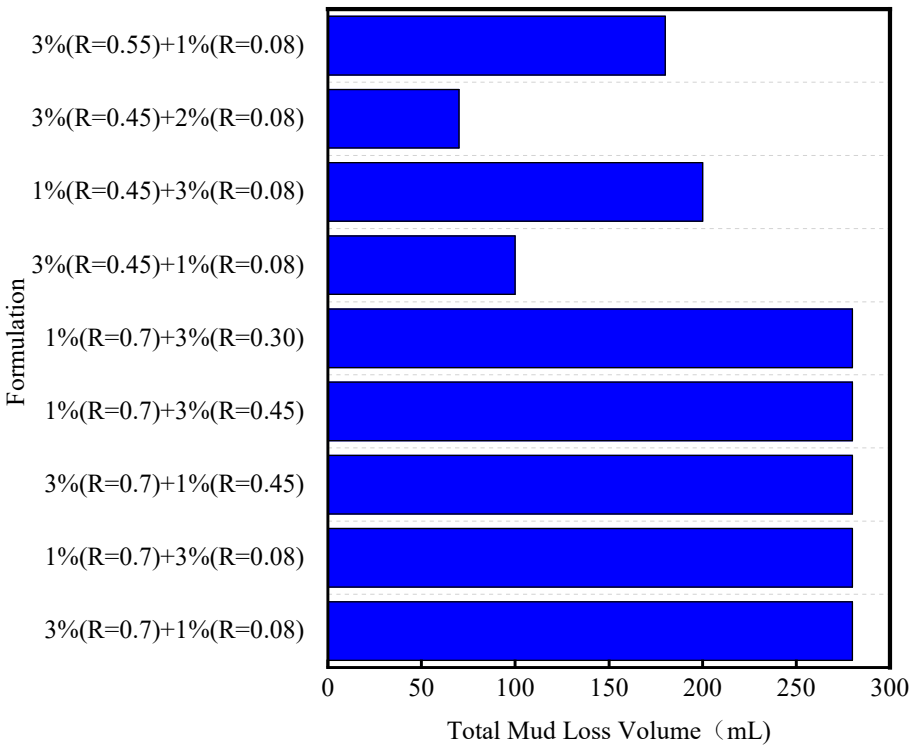



**Figure 5.** Effect of binary particle size plugging particle combinations on total lost volume.

In summary, binary particle size combinations can improve the sealing effect to a certain extent, but due to the lack of particles of specific sizes to optimize the bridging structure or filling efficiency, the overall sealing effect is still limited.

### *3.3. Bridging Mechanism of Triple Particle Size Plugging Particles*

#### 3.3.1. Effect of Size of Large and Medium Particles on Lost Volume

Figure 6 shows the impact of compounding triple particle size plugging materials on the total fluid loss. It can be seen that the total lost volume in all triple particle combination experiments is less than 200 mL. This indicates that the combined composition of large, medium, and small particles can significantly improve bridging and plugging efficiency, achieving effective sealing of lost circulation fractures. However, when the size of large particles is too large (corresponding to the data for R = 0.8 and 0.9 in Figure 6), some particles may be intercepted or obstructed at the fracture inlet, affecting their smooth entry into the fracture interior. This prolongs the time required for the lost circulation fracture to be bridged and sealed, and leads to a larger total lost volume. This phenomenon is mainly attributed to the large aspect ratio characteristic of rigid LCMs. The size of the largest particles also plays a critical role in the efficiency of primary bridge formation. Particles with an R-value close to 0.70 were optimally sized for initiating a robust primary bridge in our experimental setup, leading to rapid sealing and minimum lost volume. When the size of large particles is too small (corresponding to the data for R = 0.55 in Figure 5), it affects the bridging speed, and the final lost volume is also relatively high. Overall, for lost circulation fractures of a certain width, the bridging and sealing effect of triple particle size combined plugging materials is significantly better than that of binary particle size combined plugging materials.

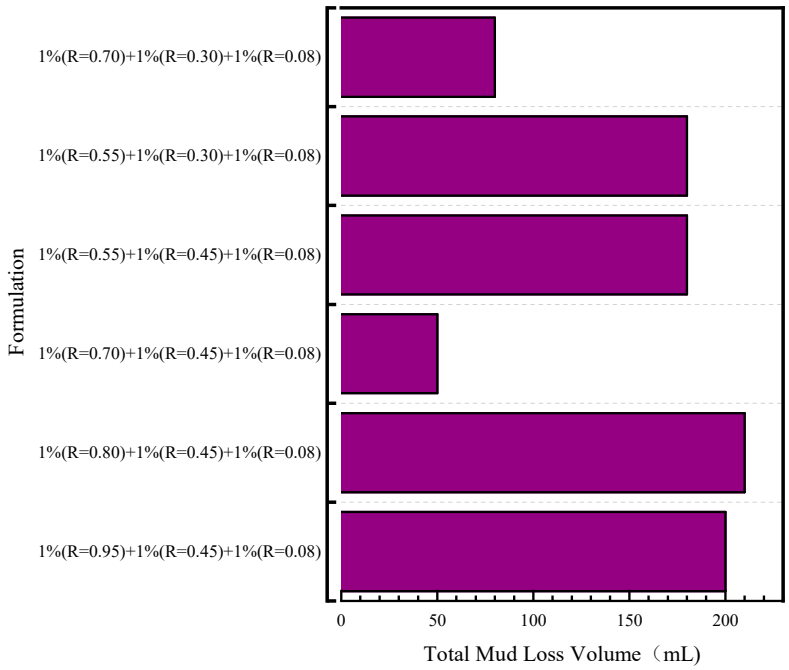



**Figure 6.** Effect of triple particle size plugging particle combinations on total lost volume.

### 3.3.2. Effect of the Percentage Content Ratio (λ) of Large and Medium Particles on Final Lost Volume

To further enhance the sealing effect of triple bridging and plugging particles on fractures, this study further investigated the influence of the proportion of triple bridging and plugging particles on the total lost volume. Figure 7 reveals the influence of the percentage ratio of large particles to medium particles (λ) on the final lost volume. Here, the percentage ratio λ is defined as the ratio of the percentage content of large particles to the percentage content of medium particles in the compounded mixture: λ = (%Large Particles)/(%Medium Particles).

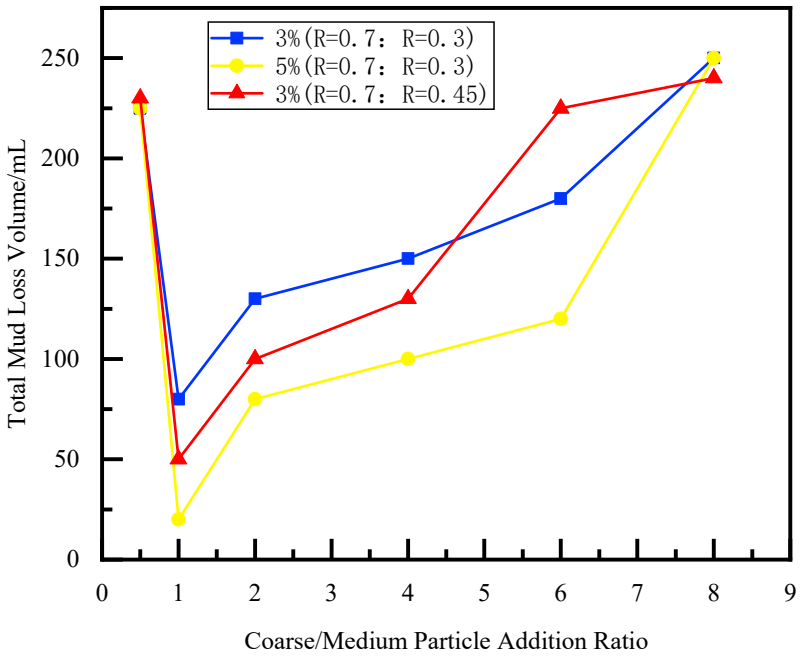



**Figure 7.** Effect of the percentage ratio of large to medium particles (λ) on total lost volume.

When λ > 1: As the value of λ increases, the total lost volume shows a trend of slow increase. λ > 1 means that the compounded plugging material contains more large particles, while the content of medium and small particles is relatively low. In this case, although the initial bridging speed is relatively fast, due to the lack of sufficient medium and small particles to fill the bridging pores between the large particles, the formed sealing layer has larger pores and lower flow resistance, which leads to a gradual increase in lost volume.

When λ < 1: The lost volume increases sharply. λ < 1 means that the compounded plugging material contains fewer large particles, which are insufficient to quickly establish an effective bridging structure within the fracture. At the same time, a large number of medium and small particles will be lost with the fluid, unable to effectively fill the pores within the fracture. Therefore, in this case, it takes longer for the plugging material to form an effective sealing layer within the fracture, resulting in a larger overall lost volume.

When λ = 1: The lost volume reaches a minimum (as shown in Figure 7). This indicates that at this ratio, the content of large and medium particles is balanced to both ensure rapid initial bridging of the lost circulation fracture (primarily driven by large particles and assisted by medium particles) and provide sufficient medium and small particles for secondary filling or bridging of the pores within the initial bridge. This synergistic effect achieves an efficient plugging outcome by forming a denser, less permeable sealing layer more quickly.

It can be inferred that in lost circulation fractures, some large particles will be blocked earliest at the fracture front during migration, providing "obstacles" for other large or medium particles to establish bridging. Subsequently, medium particles further fill or bridge within the pores of the large particles, performing secondary compartmentalization of the space within the lost circulation fracture. Finally, small particles fill in the established bridging pores, further reducing the fluid flow space and increasing flow resistance. This process aligns with the multi-stage filling model in particle packing theory. In summary, the percentage ratio of large particles to medium particles (λ) has a significant impact on the lost volume. When λ = 1, the lost volume is minimized, indicating that the particle size combination at this point can achieve the optimal bridging and filling effect.

#### 3.3.3. Effect of Small Particle Size and Its Percentage Content on Lost Volume

Figure 8 shows the influence of small particle size on the total lost volume. It can be seen that as the size of small particles decreases, their bridging and sealing effect when combined with large and medium particles gradually decreases. Only when the small particle size is R = 0.08, after mixing with the already combined large and medium particles, the plugging effect is optimal, and the lost volume is minimal. Figure 9 shows the influence of the percentage of small particles on the total lost volume. It can be seen that when the percentage of small particles is around 30%, the lost volume reaches a minimum. From this, the following can be inferred:

Regarding the influence of small particle size: When the small particle size is too small, particles easily pass through the composite pores formed by large and medium particles, making it difficult to effectively fill or retain within the existing bridging pores. In this case, small particles cannot fully achieve their filling role, leading to insufficient compactness of the sealing layer, reducing the sealing effect. When the small particle size is R = 0.08, its size is moderate and can effectively fill the pores between large and medium particles, forming a more compact sealing layer, achieving the optimal plugging effect.

Regarding the influence of small particle percentage: When the percentage of small particles is too low, there are not enough particles to fill or remain within the existing bridging pores, leading to a higher porosity of the sealing layer, lower flow resistance, and increasing the total lost volume. When the percentage of small particles is too high,

the bridging speed is slow, and the lost volume is also large. This is because the total amount of plugging material added is fixed, and adding too many small particles will lead to a reduction in the content of large and medium particles. This consequently affects the primary bridging speed, prolongs the time for the lost circulation fracture to be sealed, and leads to an increase in the total lost volume. When the percentage of small particles is around 30%, it can both ensure the initial primary bridging speed and ensure that the existing bridging pores are densely filled by small particles, achieving efficient bridging and plugging.

In summary, the size and percentage of small particles have a significant impact on the sealing effect of lost circulation fractures. Only when the small particle size is R = 0.08 and the percentage is 30% can the goal of efficient bridging and sealing of lost circulation fractures be achieved, while ensuring both the initial primary bridging speed and the dense filling of existing bridging pores by small particles.

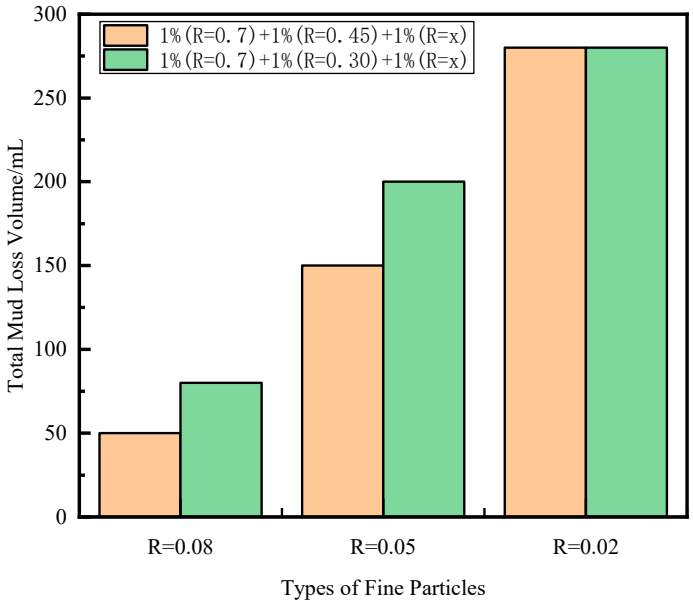



**Figure 8.** Effect of small particle size on total lost volume.

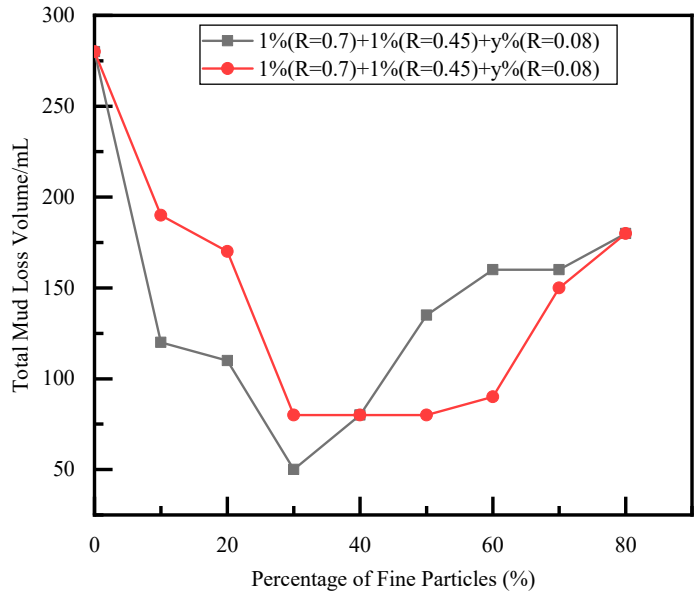



**Figure 9.** Impact of small particle percentage content on total fluid loss.

### *3.4. Quantitative Compounding Relationships for Rigid Bridging Plugging Particles in Fractured Lost Circulation*

The quantitative compounding relationships of rigid bridging plugging particles were analyzed through experiments as described above, aiming to optimize the plugging effect in fractured lost circulation formations. The research results indicate that when the plugging material contains triple rigid plugging particles, and the particle size-to-fracture width ratio satisfies R1 (R = 0.7): R2 (R = 0.45~0.3): R3 (R = 0.08) ≈ 1:1:1, the compounded plugging material can achieve efficient bridging within the fracture. Furthermore, the concentration of the plugging material is crucial for bridging efficiency, and its influence on the total lost volume needs further investigation. Figure 10 shows the influence of the total concentration of plugging material on the total lost volume.

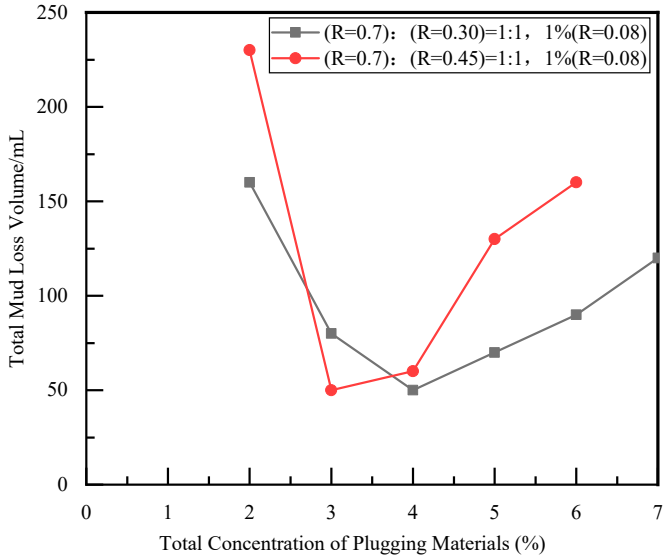



**Figure 10.** Total lost volume effect of total concentration of triple plugging particles on lost volume.

Figure 10 demonstrates the influence of the total concentration of plugging material on the total lost volume. The research findings are as follows:

- When the total concentration of plugging material is too high, the interaction between plugging particles at the fracture inlet significantly increases. This excessive interaction leads to particle accumulation at the fracture inlet, prolonging the time required for particles to enter the fracture interior and establish bridging. Therefore, the final total lost volume increases.
- When the total concentration of the compounded plugging material is too low, the number of bridging particles entering the fracture decreases, and the interaction forces between particles weaken. In this case, it is difficult to meet the conditions for forming stable bridging in a short time, increasing the total lost volume.
- When the triple particles in the plugging material satisfy R1 (R = 0.7): R2 (R = 0.45~0.3): R3 (R = 0.08) ≈ 1:1:1 and the total concentration is around 4%, the compounded plugging material can achieve efficient bridging within the fracture and effectively prevent drilling fluid loss. At this point, the choice of optimal concentration balances particle packing theory and fluid mechanics principles.

To verify the reliability of the aforementioned quantitative relationship for compounding plugging particles, this study further conducted plugging experiments on three types of lost circulation fractures with inlet widths of 2 mm, 4 mm, and 5 mm. The experimental results are shown in Table 1. From the final lost volume data in Table 1, it can be seen that the plugging formula designed based on the above relationship achieved

efficient sealing for both 2 mm and 4 mm fractures, indicating the good applicability of this compounding relationship.

**Table 1.** Experimental results of plugging leak-off fractures with different widths.

| Number | Fracture Width (mm) | Base Formulation | Total Lost Volume (mL) |
|---|---|---|---|
| 1 | 2 | 1%0.7 + 1%0.45 + 1%0.25 | 30 |
| 2 | 4 | | 80 |
| 3 | 5 | | 230 |
| 4 | 2 | 1%0.7 + 1%0.3 + 1%0.25 | 28 |
| 5 | 4 | | 90 |
| 6 | 5 | | 230 |

The 'Base Formulation' used for these validation experiments was designed by applying the optimal R-value principle obtained from the initial experiments (R1 ≈ 0.7, R2 ≈ 0.45~0.3, R3 ≈ 0.08) to the specific fracture width being tested, selecting available particle grades from our 12 options with D50 values closely matching the calculated target sizes for large, medium, and small particles, and compounding them at the 1:1:1 ratio with a total concentration of 4%. For instance, for the 2 mm fracture, the target D50s were approximately 1.4 mm (R = 0.7), 0.6–0.9 mm (R = 0.3–0.45), and 0.16 mm (R = 0.08), and corresponding available particle grades were selected. The experimental results are shown in Table 1. From the final lost volume data in Table 1, it can be seen that the plugging formula designed based on this relationship achieved efficient sealing for both 2 mm and 4 mm fractures (with total lost volumes below 100 mL, indicating effective plugging), indicating the good applicability of this compounding relationship across a range of medium-scale fracture widths. The slightly higher lost volume for the 5 mm fracture (230 mL) suggests that while the principle remains valid, larger fractures may require adjustments in total concentration or could potentially benefit from additional design considerations beyond this specific optimal ratio and concentration, such as a higher proportion of larger particles or initial sweeping with coarser material before applying this refined mix; these factors warrant further investigation.

The aforementioned compounding relationship implies that the particle size distribution of bridging and plugging materials should exhibit three characteristic peaks, respectively corresponding to plugging particles with large, medium, and small particle size-to-fracture width ratios. In fact, the ultimate goal of lost circulation control is to achieve dense packing of the plugging material within the fracture, forming a dense sealing layer, thereby effectively preventing the passage of drilling fluid. This means that in order to establish a dense sealing layer within the fracture, the size of the plugging particles must conform to particle packing theory. The Fuller curve in particle packing theory indicates that the bridging skeleton formed by particle materials within the fracture is the basis for achieving pressure-bearing sealing. The characteristics of gradual accumulation of a large number of plugging particles within the fracture are highly similar to the phenomenon of dense particle packing; therefore, particle packing theory can be used to explain the accumulation behavior of plugging particles. This theory includes discontinuous packing models and continuous packing models, among which the continuous packing models are primarily described using the Andersen equation and the Fuller curve.

The Fuller curve is the ideal grading curve proposed by Fuller and Thompson [16] and is expressed as follows:

$$P(D_x) = 100\left(\frac{D_x}{D_{\max}}\right)^{0.5}. \quad (1)$$

where $P(D_x)$ is the cumulative percentage of particles smaller than Dx (%), $D_x$ is particle size (mm), and $D_{max}$ is maximum particle size (mm).

Based on the aforementioned compounding relationship, this study plotted the cumulative particle size distribution curve of the lost circulation material, with the particle size-to-fracture width ratio as the x-axis and cumulative particle size distribution as the y-axis, and compared it with theoretical values. As shown in Figure 11, the cumulative particle size distribution curve based on the Fuller curve is basically consistent with the experimental cumulative particle size distribution curve of the plugging particles. This indicates that the lost circulation material designed using the quantitative compounding relationship for LCMs obtained in this study can form a dense sealing layer within the fracture through bridging (see Figure 12), thereby effectively preventing the loss of drilling fluid. In summary, this study further validated the quantitative compounding relationship for rigid bridging plugging particles in fractured lost circulation through plugging experiments with different fracture widths and particle packing theory.

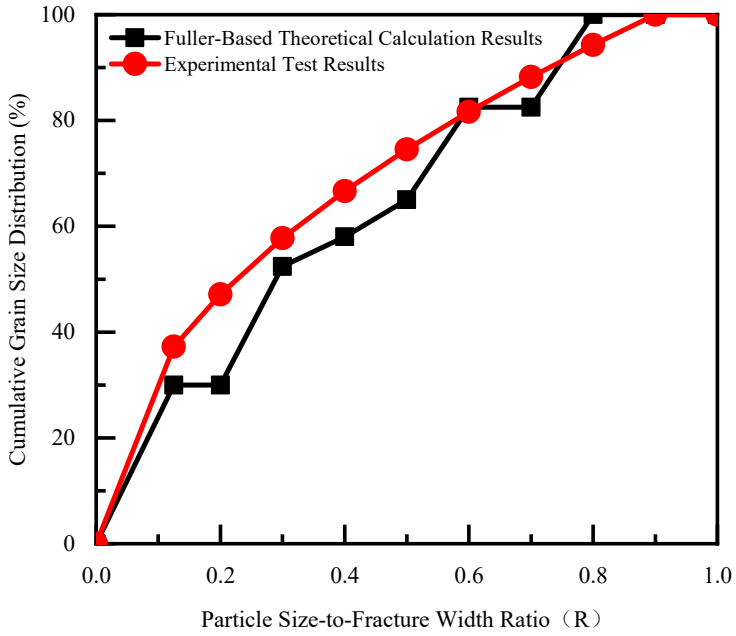



**Figure 11.** Cumulative particle size distribution curve.

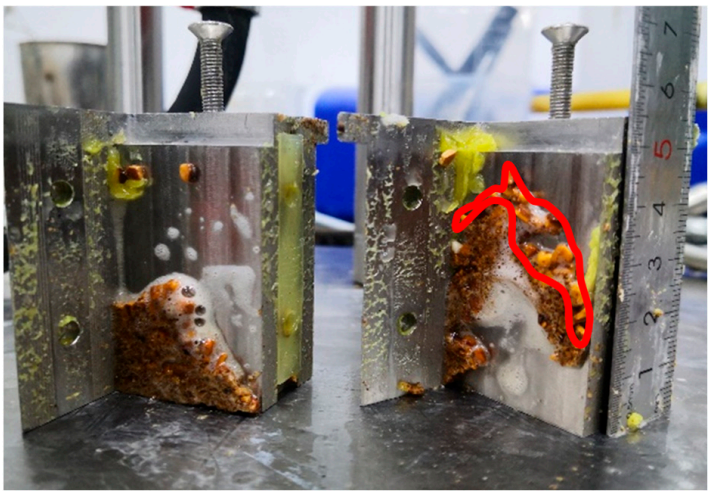


**Figure 12.** Plugging layer photograph. The red area represents the blocked layer bridging zone.

The above research indicates that when the particle size distribution of LCMs for fractured formations exhibits three characteristic peaks (corresponding to the particle size-to-fracture width ratios of large, medium, and small plugging particles) and the total concentration is maintained at around 4%, the compounded plugging material can efficiently establish bridging and form a dense sealing layer within the fracture. This finding not only provides a solid scientific basis for efficient sealing of fractured lost circulation formations but also provides important theoretical support for the design of plugging formulas in actual engineering applications. However, it is worth noting that as the complexity of the formation fracture width distribution increases, the particle size distribution of the plugging particles should also become correspondingly more complex. In some cases, when the particle size distribution has more characteristic peaks (i.e., is multi-modal), the compounded plugging material may be able to achieve a greater fracture sealing effect. Therefore, future research can further explore the impact of multi-modal particle size distribution on the sealing effect of complex fracture networks, in order to develop more adaptable and efficient lost circulation material formulas.

It is important to note that while this study provides a quantitative design principle based on optimal particle size ratios relative to fracture width, practical field applications must also consider operational constraints, particularly the pumpability of the LCM formulation through surface equipment (pumps, pipelines, screens) and downhole tools (LCM subs, MWD/LWD tools). The maximum particle size must be compatible with the narrowest restriction in the circulation system to prevent plugging. In the field, the estimated fracture width is used with the R-value principle to determine target particle sizes, and then commercially available LCM products with particle size distributions best approximating these targets, within the constraints of pumpability, are selected and compounded at the recommended ratio and concentration. The 12 size grades used in this experimental study were primarily for detailed investigation of bridging mechanisms across a wide range of R-values; practical field formulations would typically utilize a smaller number of specific product grades selected based on the required target sizes and pumpability limits. Future research could include developing charts or software tools that integrate these operational limits with the R-value design principle for direct field use.

## 4. Conclusions

A systematic exploration of the quantitative relationships for compounding multi-sized rigid bridging plugging materials was conducted, yielding the following main conclusions:

(1) When three different particle size levels of rigid plugging material (selected based on specific particle size to crack width ratios R1 $\approx$ 0.7, R2 $\approx$ 0.45~0.3, R3 $\approx$ 0.08) are mixed at an approximate 1:1:1 ratio by weight [or volume, clarify how ratio is measured], and the total concentration is controlled at approximately 4%, the plugging effect is optimal for medium-scale fractures, and the leak-off volume is significantly reduced. This provides clear quantitative guidance for optimizing plugging formulations by relating particle size directly to the estimated fracture width.

(2) This optimal ratio results in the particle size distribution of the plugging material exhibiting multiple peaks, forming multi-modal distribution characteristics. This means that particles of different sizes can synergistically work together in cracks of different sizes, quickly forming a dense, low-permeability plugging layer. This mechanism is highly effective for plugging in fractured formations, ensuring rapid bridging and maintaining low permeability of the plugging layer.

(3) Different from traditional methods that only rely on the overall particle size distribution, the proposed quantitative relationship emphasizes selecting specific particle

size levels based on the particle size to crack width ratio and accurately determining the dosage of each particle size level of plugging material, as well as the total concentration after compounding. Therefore, this quantitative relationship can be directly applied to plugging formulation design, significantly reducing tedious experimental verification and improving design efficiency and reliability.

(4) This quantitative relationship provides a solid scientific basis for the design of rigid LCMs in fractured formations and can serve as the foundation for developing practical field tools, such as a workflow chart or algorithm, to guide LCM selection, particle size proportioning, and concentration adjustment based on estimated fracture characteristics. For situations with complex geological environments and a large span of crack widths, the adaptability of this quantitative relationship requires further in-depth study. Subsequent research will continue to report relevant progress.

**Author Contributions:** W.W.: Investigation, Writing—review and editing. Y.Z. (Yuxuan Zheng): Methodology, Supervision. C.M.: Conceptualization, Visualization, Writing—original draft. J.C.: Supervision. Y.Z. (Yi Zhang): Supervision. T.L.: Data curation. M.L.: Methodology, Supervision. All authors have read and agreed to the published version of the manuscript.

**Funding:** The authors gratefully express their thanks for the financial supported by Deep Earth Probe and Mineral Resources Exploration-National Science and Technology Major Project (Grant No. 2024ZD1000901, 2024ZD1000806),the CNPC Innovation Fund (NO. 2024DQ02-0149), the China Scholarship Council: The State Scholarship Fund (202308370229), and the Technology Innovation Center for Carbon Sequestration and Geological Energy Storage, Ministry of Natural Resources (MNRCCUS062301).

**Data Availability Statement:** The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

**Conflicts of Interest:** Author Chen Jianguo was employed by the Daqing Drilling Engineering Company, No. 2 Drilling Company. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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