Experimental investigation of dynamic mechanical characteristics of inhomogeneous composite coal-sandstone combination for coalbed methane development

Yunchen Suoa,c, Ning Luoa,b,c,*, Yabo Chai a,c, Haohao Zhang a,c, Cheng Zhaid,**, Weifu Sunb,***

HIGHLIGHTS

• Two types of coal-rock combination were used to analyze dynamic mechanical properties and damage mechanism.
• The dynamic mechanical behavior of the two combinations were analyzed for the strain rate effects and structural effects.
• High-speed photography was used to obtain the fracture initiation and failure patterns of the two composites.
• The improved constitutive model based on the ZWT was significantly consistent with the two combined bodies.

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ABSTRACT

In deep resource exploitation, the coal seam and the strata are jointly loaded, forming a systematic combined structure that can have a significant effect on coalbed methane (CBM) development. Therefore, to understand the deformation and damage characteristics due to blasting load of the complex and real ground conditions, the 50 mm split Hopkinson pressure bar (SHPB) was used to study the dynamic performance and energy changes of coal-sandstone combination and sandstone-coal combination as inhomogeneous materials. In addition, high-speed photographic equipment was employed to determine the damage failure mechanisms. The results showed that the dynamic compressive strength and failure strains of two combinations showed polynomial relationships with increasing strain rates. The strain rate effects and likenesses of the two combinations' energy and energy rates were substantial. Furthermore, for the coal-sandstone combination, the initial damage fractures occurred at the end face near the bar, and at the interface for the sandstone-coal combination. Eventually, the improved constitutive model based on the ZWT was significantly consistent with the two combinations. The related theory can perform an effective and practical role in the mining of coal rocks under complex ground conditions for CBM development.

1. Introduction

Nowadays, as coal mining continues to go deeper, dynamic disasters such as rock-burst, coal and gas protrusion are becoming more common [1, 2]. The essence of these dynamic hazards is the instability and deformation of the entire mechanical system of the coal mine due to the invalidation of the combined structure of multitype rocks [3, 4, 5]. The conventional mining technology process causes damage to the coal body, as well as the top and bottom plates, which impacts the overall instability [6, 7, 8]. The properties of the combined structure of coal and sandstone, as typical inhomogeneous quasi brittle materials, exhibits considerably different characteristics than the monomer. Therefore, it is critical to
investigate the dynamic properties of the coal-rock combined structure to comprehend the structural stability and damage forms in order to prevent dynamic disasters.

Up to now, many scholars have also conducted not only on a single rock but also start to consider the mechanical characteristics of the coal seam and its top and bottom slab under combined action. In the study of rock statics, Huang and Liu [9] investigated the uniaxial compression tests of the coal-rock combined structure under different loading rates. The results revealed that the mechanical properties of the combined structure, such as the elastic modulus, peak stress, were better than the coal and lower than the rock. Zhang et al [10] used PFC to evaluate the mechanical response of the coal-to-overall height ratio and loading rate on the coal-rock combination. The results showed that the damage developed first in the coal and subsequently spread to the rock or the entire structure. Through tests and computational analysis, Chen et al. [11] also concluded that the buckling failure and the deformation damage of coal-rock combination were mostly controlled by coal, and the overall mechanical properties are between coal and rock. Then, Liu et al. [12] established the dynamic damage constitutive model of coal and rock combination by combining the damaged body and Newton body. In terms of rock dynamics, Gong et al [13] studied the variation of the dynamic mechanics and energy of coal-rock combinations under different strain rates using the SHPB test system. The related studies concluded that the stress-strain curve of the coal-rock combination showed an obvious bimodal distribution, and its compressive strength, failure strain, reflected energy showed obvious strain rate effects. Additionally, the dynamic instability failure of the coal-rock combination was still primarily dominated by coal. Yang et al [14] found that the dynamic compressive strength and failure strain of the coal-rock combination showed also an obvious strain rate effect. Furthermore, the macroscopic fracture initiation of the coal-rock combined body was found to occur predominantly at the coal or rock ends far away from the coal-rock interface by high-speed photography. Miao et al [15] employed SHPB to perform dynamic mechanical study on the coal-rock-coal combined body and discovered that mechanical parameters such strain rate, strain, stress, dynamic elastic modulus, and fragmentation are sensitive to impact load.

The preceding studies examined not just a single rock body, but also considered the necessity of investigating the mechanical behaviors of the coal-rock combination. However, the previous research only focused at a certain coal-rock combination structure. Therefore, on the basis of the former research, two types of composite structures, coal-rock and rock-coal, were comparatively studied. Peak strength, failure strain, and energy of both were studied in terms of strain rate. The failure mechanisms of both combinations were compared using high-speed photography equipment. Furthermore, the ZWT constitutive model was improved to properly represent two coal rock combinations. The above research can more effectively analyze the realistic mechanical characteristics of coal-rock combinations under complicated geological conditions, as well as provide theoretical support for the CBM effective development.

| Table 1. Specific dynamic parameters of coal and red sandstone. |
|----------------|-----------------|-----------------|-----------------|-----------------|
| Type           | Density         | Compressive strength | Failure strain | Elasticity modulus |
| Coal           | 1.26 g/cm³      | 20.7 MPa          | 0.007          | 2.37 GPa        |
| Red sandstone  | 2.41 g/cm³      | 56.2 MPa          | 0.006          | 13.84 GPa       |

2. Experimental

2.1. Specimens preparation

As shown in Figure 1, the coal and red sandstone were selected to make the samples for combinations. First, the coal samples and red sandstone samples used in the SHPB test were processed into the standard sizes of 50 mm diameter and were 25 mm height. In addition, all samples were polished to ensure that the surface finish and flatness of the two loading surfaces were less than 0.02 mm [16, 17]. To make the coal rock combined body with diameter and height of 50 mm and 50 mm, the acrylic resin was used to coat the end face of the specimen to ensure even application and no overflow of glue [14, 18]. Then according to the use of the requirements of the environment at about 10 °C placed in 24 h. When the bonding was formed, it was polished smooth again to ensure that its flatness and verticality fulfilled the standards. There are two types of combination structures: coal-rock combination (coal close to the incident bar) and rock-coal combination (rock close to the incident bar). For convenience, the coal-rock combination and the rock-coal combination are abbreviated as C-R combination and R-C combination, respectively.

The dynamic mechanical characteristics of 50 mm × 50 mm coal and red sandstone samples were measured using 0.3MPa impact pressure. The specific parameters are shown in Table 1.

2.2. SHPB test system

The 50 mm SHPB test system is shown in Figure 2. The whole test system includes launcher, impact bar, incidence bar, transmission bar, buffer bar, laser velocimeter, and dynamic test analyzer composition. The special parameters of the bar were shown in Table 2. The resolution of high-speed photography was set to 800 × 600, and the sampling frequency and exposure time were 11,000 pps and 90.457 us respectively.

2.3. Experimental method

Subhash et al. [19] showed that for brittle materials, stress waves need to be reflected back and forth within the specimen for 3 to 5 round trips. To test the stress balance, rubber material was used as the wave-form correction in this experiment. Figure 3(a) and (b) shows the stress wave verification curves for the representative C–R combination and the R–C combination, and the results can be considered that the stress waves satisfied during the test fulfill Eq. (1). Therefore, the two-wave method is

| Table 2. Specific SHPB bar parameters. |
|----------------|-----------------|-----------------|-----------------|-----------------|
| Parameters     | Material        | Impact bar      | Incidence bar   | Transmission bar |
| Value          | Silicon-manganese spring steel | 500 mm          | 3000 mm         | 3000 mm         |
| Parameters     | Buffer bar      | Poisson’s ratio | Elastic modulus | Density         |
| Value          | 1200 mm         | 0.29            | 210 GPa         | 7800 kg/m³      |
| Parameters     | P-wave velocity | Tensile strength| Yield strength  | Reduction of area |
| Value          | 5188 m/s        | \( \sigma_u \geq 1274 \) MPa | \( \sigma_y \geq 1176 \) MPa | \( \psi \geq 25\% \) |
used instead of the three-wave method, i.e., Eqs. (2), (3), and (4) can be reduced to Eqs. (5), (6), and (7) [20, 21].

\[ \varepsilon_I + \varepsilon_R = \varepsilon_T \]

\[ \sigma_s = \frac{A_B}{2A_S} E_0 (\varepsilon_I + \varepsilon_R + \varepsilon_T) \]

\[ \dot{\varepsilon}_s(t) = \frac{C_0}{L_s} (\varepsilon_I - \varepsilon_R - \varepsilon_T) \]

\[ \varepsilon_s = \int_0^t \dot{\varepsilon}_s(t) dt \]

\[ \sigma_s = \frac{A_B}{A_S} \varepsilon_T \]

\[ \dot{\varepsilon}_s(t) = -2 \frac{C_0}{L_s} \varepsilon_R \]

Figure 2. SHPB and high-speed camera test system.

Figure 3. Uniformity verification. (a) Verification of C–R. (b) Verification of R–C.

Figure 4. Strain rate curve of the representative sample.
\[ \varepsilon_S = -2 \frac{C_0}{L_0} \int_0^t \dot{\varepsilon}_d \, dt \]  

(7)

where, \( \varepsilon_I \), \( \varepsilon_R \) and \( \varepsilon_T \) are incident strain pulse, reflected strain pulse and transmitted strain pulse respectively; \( A_B \) and \( A_S \) are the cross-sectional areas of the bar and the specimen respectively; \( \sigma_0 \), \( \varepsilon_S(t) \) and \( \varepsilon_d \) are the stress, strain rate and strain of specimen respectively, and \( C_0 \) are the elastic longitudinal wave velocity of the bar; \( L_S \) is the initial length of the specimen.

The strain rate of the test data can be calculated using Figure 4 and Eq. (8). It can be seen that throughout the test process, the AB section exhibits a plateau for about 100 \( \mu s \) of time, indicating that the material is being loaded at a consistent strain rate. Where point A represents the point at which the specimen reaches stress uniformity and point B represents the point at which the specimen begins to break down, i.e., the peak stress [21, 22].

\[ \dot{\varepsilon} = \frac{1}{n} \sum_{i=1}^{n} \dot{\varepsilon}(i) \]  

(8)

3. Results and discussion

3.1. Variation of stress-strain

Figure 5(a) showed the stress-strain relationship of the C–R combination, whereas Figure 5(b) showed the stress-strain curve of the R–C combination. The stress-strain curves in Figure 5(a) clearly showed a bimodal distribution, however the R–C combination in Figure 5(b) did not appear. It was caused by the excessive difference between the mechanical properties of the red sandstone and the coal, which had also been found in previous studies [13, 14]. The bimodal phenomenon gradually decreased with increasing strain rate. As the strain rate increased, the stress-strain curve of the C–R combination became much more equally distributed, while that of the R–C combination became more concentrated in a certain area. Therefore, it could be seen that the discreteness of the C–R combination was larger compared to the R–C combination.

Figure 6. Variation of compressive strength and failure strain. (a) Compressive strength of C–R and R–C. (b) Failure strain of C–R and R–C.
3.2. Variation of compressive strength and failure strain

As shown in Table.1, the dynamic compressive strengths of coal and red sandstone were 20.7 MPa and 56.2 MPa, respectively, as measured by the 0.3 MPa impact pressure. While the strain rate of two combined bodies measured at 0.3 MPa was about 60–90 s\(^{-1}\), i.e., the compressive strength was about 28–35 MPa. This indicated that the peak stress of the two combined bodies was between coal and red sandstone, which was the same as the previous studies [10, 11].

When the strain rate effects of the dynamic compressive strength and failure strain of the C–R and R–C combined bodies were analyzed, it was found that the compressive strength and failure strain of two structures showed the significant polynomial relationship with the strain rate. The compressive strength and failure strain of the C–R combination showed a 6-fold relationship with strain rate, and the R–C combination showed a 5-fold relationship. From Figure 6(a), it could be seen that as the strain rate increased, the platform stage appeared in both the C–R combination and the R–C combination, and that of the C–R was a little shorter. Moreover, the platform stage of the failure strain for the C–R combination in Figure 6(b) also showed slight fluctuations, which was due to the C–R being more discrete and influenced by external forces. In contrast, the failure strain of the R–C showed a better phase with the increasing strain rate, and both the compressive strength and the failure strain showed a clear plateau in the strain rate interval of 65–95 s\(^{-1}\). Thus, the curve could be divided into three phases, with I and III being fast-rising phases and II being a platform stage.

3.3. Variation of energy and energy rate

Xie et al. [23] pointed out that the nature of rock destabilization damage was the evolutionary process of energy release and dissipation. Therefore, it was also of enormous engineering significance to study the strain rate effects of various energies. The relevant calculation formulas were shown in Eqs. (9), (10), and (11). As could be seen from Figure 7(a) and Figure 8(a), the reflective energy of the C–R and R–C showed a clear linear relationship with increasing strain rate. While the reflective rate of the C–R combination showed a clear W-shape, the reflective rate of the R–C combination showed alternating fluctuations of increase and decrease. As shown in Figure 7(b) and Figure 8(b), the transmitted energy and transmitted rate of two combined structures followed the same trend before the turning point. However, the C–R combination showed a clear divergence in the values at a strain rate of about 90 s\(^{-1}\), and the transmitted rate was sharply downward. This pattern also appeared in the R–C combination, where the energy transmitted rate turned at a strain rate of about 60 s\(^{-1}\). The absorbed energy and absorbed rate of the two combinations showed agreement respectively in Figure 7(c) and Figure 8(c), and there was also a high likeness in the trend of the two combinations with each other. Although the absorbed rate of the C–R
combination showed generally W-shape, there was also a decreasing trend in the strain rate of $50–55 \text{s}^{-1}/C_0$. Therefore, it could be assumed that the absorbed energy and absorbed rate of both combinations showed the same fluctuation. The relationship between its reflective rate and absorbed rate showed negatively correlated variations. The $R-C$ combination and $C-R$ combination also showed alternating variations in the form of increases and decreases, with minimal value of energy reflective rate at strain rate about $70$ and $105 \text{s}^{-1}/C_0$, while the maximal value of absorbed rate here.

Additionally, as shown in Figure 7(d) and Figure 8(d) that in the percentage of energy, the transmitted rate of the $C-R$ combination is $5\%–18\%$, with the majority being around $10\%$. The minimum transmitted rate of the $R-C$ combination is $4\%$ and the maximum is $23\%$. It is evident that the $R-C$ combination could transmit more energy.

\begin{align}
W_x &= A_x C_0 \frac{\int_0^t \sigma_I^2(t) \, dt}{E_s} - A_x C_0 \frac{\int_0^t \epsilon_I^2(t) \, dt}{E_s} \\
W_A &= W_I - (W_R + W_T) \\
\lambda_y &= \frac{W_I}{W_T} \times 100\% 
\end{align}

where, $x = I, R$ and $T$. $W_t$, $W_r$ and $W_f$ are incident stress wave energy, reflected stress wave energy, and transmitted stress wave energy respectively. $\sigma_I$, $\sigma_R$ and $\sigma_T$ are the stress time history of incident stress wave, reflected stress wave, and transmitted stress wave respectively. $W_I$ is absorbed stress wave energy. $y = R, T, A$. $\lambda_r$ and $\lambda_A$ are the ratio of reflected stress wave energy, transmitted stress wave energy, and absorbed stress wave energy to the incident stress wave energy respectively.

### 3.4. Crack propagation pattern

The damage forms of the two combination structures at different speeds were obtained by high-speed photography. It could be seen in Table 3 that the coal was destroyed in advance for both the $R-C$ and the $C-R$, indicating that the failure of the combination was dominated by coal [13]. For the $C-R$ combination, at the bullet speed of $4.768 \text{ m/s}$, the bulge cracking ejection appeared, however only the end face was broken. When the velocity increased, the splitting damage began to appear but eventually presented mixed damage of tensile and splitting. When the speed reached $7.494 \text{ m/s}$, the degree of coal crushing intensifies, and the specific form of damage was no longer observed. Furthermore, it was noteworthy that at this time, the red sandstone cracks at the end face and presented splitting damage. For the $R-C$ combination, the compression process of the
coal was simpler to visualize. At a speed of 4.983 m/s, the coal first showed multiple splitting damage, followed by fragmentation ejection, and finally the same mixed damage of splitting and stretching. With the increase of speed, both the coal and the red sandstone began to show cracks. The coal showed cracks at the end face, while the red sandstone showed cracks at the interface. And the cracks in the coal sample began to develop toward the cracks of the red sandstone. While the cracks of the red sandstone also began to cross the interface and continued to develop and finally showed splitting and shear damage. When the speed was 7.66 m/s, the coal started to show partial fragmentation at the interface, followed by explosive crushing damage. While the red sandstone also started to show splitting cracks at the intersection, and finally evolved into the form of splitting tensile fragmentation damage.

It could be seen that the cracks in the C–R tend to appeared at the coal or rock ends away from the coal-rock interface, especially coal. From the beginning of the bulging debris ejection, obvious defects appeared, and the resulting development of cracks and eventual destruction. In contrast, the fragmentation of red sandstone in the R–C emerged earlier than that of the C–R, and the cracks frequently appeared at the intersection. The overall damage was greater and the damage form was more complicated. At the same speed, the rock component of the R–C combination played a more energy accumulation and transmission role. It showed that the rock mode changed from splitting damage to shear damage, the energy appeared to transfer to the coal. The coal body damage degree gradually increased, and the coal sample broken particles gradually transitioned from lumpy to powdery [14].

| Number | Speed(m/s) | The image got by high-speed photography |
|--------|------------|----------------------------------------|
| C-R-1  | 4.768      | ![Image](image1.png)                   |
| C-R-2  | 5.611      | ![Image](image2.png)                   |
| C-R-3  | 7.494      | ![Image](image3.png)                   |
| R-C-1  | 4.983      | ![Image](image4.png)                   |
| R-C-2  | 5.629      | ![Image](image5.png)                   |
| R-C-3  | 7.664      | ![Image](image6.png)                   |
3.5. Establishment of the dynamic constitutive model

The ZWT is a dynamic constitutive model, which was often used to describe rock or concrete. The ZWT is made up of one nonlinear spring and two Maxwell bodies with different characteristic times in parallel. The detail was shown in Eq. (12) [24].

\[
\sigma = E_0 \dot{e} + E_1 \int_0^t \exp \left( -\frac{t-r}{\varphi_1} \right) dr + E_2 \int_0^t \exp \left( -\frac{t-r}{\varphi_2} \right) dr
\]

(12)

where, \(E_0 \dot{e} + E_1 \beta \varepsilon^3\) is used to describe equilibrium stress; \(E_1\), \(\alpha\), \(\beta\) is the elastic coefficient of non-linear spring, and are used to describe the viscoelastic response with low and high-frequency relaxation time, respectively; \(E_1\) and \(E_2\) are the elastic constants of the corresponding low and high-frequency Maxwell bodies respectively, \(\varphi_1\) and \(\varphi_2\) are the characteristic time.

Given the following reasons,

1. The stress-strain curve before the peak strength of the two combinations was approximately linear, with almost no fluctuation. This indicated that the failure of the combinations to break was small until the peak compressive strength was reached. Therefore, for simplicity of calculation, the first polynomial describing the equilibrium stress was simplified to a straight line. The initial phase of the stress-strain curve was simplified to linear elasticity.

2. When the SHPB was used to impact the combinations, it was found that the dynamic loading time during the test was only 10–10^2 µs. The relaxation time \(\varphi_1\) in ZWT, which represented the low frequency, was 10–10^2 s, indicating that the Maxwell unit did not have enough time to relax. Therefore, the effect of the first integral term on the overall could be ignored, the ZWT model could be simplified as Eq. (13).

\[
\dot{\varepsilon} = \dot{E}_0 e + E_1 \int_0^t \varepsilon \exp \left( -\frac{t-r}{\varphi_2} \right) dr
\]

(13)

3. The red sandstone used as the combination was very dense and had no obvious fractures. However, the coal contained a large number of pores and fractures inside. Therefore, the damage caused must be considered when examining its dynamic constitutive model. According to the Lemaitre et al. [25] strain equivalence principle, the basic equation of dynamic damage constitutive relationship of coal could be established as Eq. (14).

\[
\sigma_d = (1-D)\sigma_e
\]

(14)

where, \(\sigma_d\) is the effective stress; \(\sigma_e\) is the nominal stress; \(D\) is the damage factor. When \(D = 0\), it means that the C–R or R–C has no damage; when \(D = 1\), it means that the C–R or R–C has completely lost its load-bearing strength.

The study by Wang et al. [26] and Wang et al. [27] found that the evolution of damage presented the exponential function relationship with strain and strain rate, then the form of the damage evolution equation could be expressed as Eq. (15).

\[
D = A\varepsilon^{\lambda-1}\varepsilon^\mu
\]

(15)

According to the dynamic failure criterion, if \(D \geq D_c\), Eq. (16) can be obtained.

\[
A\varepsilon^{\lambda-1}\varepsilon^\mu \geq D_c
\]

(16)

where, \(D_c\) is the critical damage value corresponding to the critical state of material dynamic failure. According to the bivariate failure criterion, different failure strains will exist for a given particular for a given specific \(D_c\). Therefore, if \(\lambda > 1\), the sample should show the “impact embrittlement”, showing the failure strain decreasing with increasing strain rate. On the contrary, if \(\lambda < 1\), the sample should show the “impact toughening”, showing the failure strain increases with increasing strain rate [27].

When the stress-strain curve and the time course of absorbed energy were studied together in Figure 9, it was found that the absorbed energy increases with time in an S-shaped trend. Almost little energy was absorbed for damage until the critical strain \(\varepsilon_{th}\). After that, the absorbed energy increases sharply and reached the maximum at the peak stress. Therefore, it is reasonable to assume that the specimen did not absorb energy for damage until the critical strain \(\varepsilon_{th}\), at which point damage commenced.

Therefore, the improved ZWT model was shown as Eq. (17).

\[
\sigma = \begin{cases} 
E_0 \dot{\varepsilon} + E_1 \varepsilon \exp \left( -\frac{\varepsilon}{\varphi_2} \right) & \varepsilon \leq \varepsilon_{th} \\
(1-A\varepsilon^{\lambda-1}\varepsilon^\mu) \left[ E_0 \dot{\varepsilon} + E_1 \varepsilon \exp \left( -\frac{\varepsilon}{\varphi_2} \right) \right] & \varepsilon > \varepsilon_{th}
\end{cases}
\]

(17)

The viscoelastic dynamic constitutive model considering damage was shown in Figure 10.

3.6. Fitting of the present constitutive equation

In Figure 11(a) and (b), typical stress-strain curves were selected from the two combinations for fitting, and all were found to have the high
degree of fit. Table 4 shows the parameters corresponding to the damage factor. It was noteworthy that the range of $\lambda$ for the two combinations was much more than 1, indicating that the two combined structures showed impact embrittlement and that the failure strain increased as the strain rates increased. This pattern fitted with Figure 6(b) as well. Additionally, the fitting $R^2$ values are in the 0.95–0.99 range, indicating the constitutive equation’s designed to work. The related results showed that the constitutive model could respond well to the stress-strain curves of the two combinations.

4. Conclusion

(1) The stress-strain curves of the C-R combination showed the obvious bimodal distribution and were more sensitive to the strain rate. The dynamic compressive strength of the C–R and R–C was between coal and red sandstone. The compressive strengths and failure strains of both combinations satisfied polynomial relationships with increasing strain rate and could be divided into three stages, with stages I and III being the fast-rising stages and II being the flat stage.

(2) The reflective energy increased linearly with strain rate in both combinations. The transmitted energy and energy transmitted rate for the respective combinations could be consistent up to a certain strain rate, beyond which they separated. Both absorbed rates fluctuated, but the relationship between the two combinations remained stable. Furthermore, there was a significant negative relationship between the transmitted rate and the reflected rate.

(3) The dynamic damage forms of both combinations were obtained using high-speed photography. It was found that the C–R combinations generally cracked from the two end faces near the bar and then penetrated toward the middle, showing mixed damage of splitting and stretching. The damage form was dominated by coal to a large extent. In contrast, the R–C combinations were more likely to suffer interface cracking, and the red sandstone started to develop shear damage rather than splitting damage. This indicated that the rock of the R–C combination appeared to show the role of energy accumulation and conduction.

(4) The ZWT viscoelastic constitutive model was improved and fitted to represent coal-rock combinations. It was found that $\lambda$ can well reflect the strain rate effect of failure strain and both combinations were found to fit well with the construction of constitutive equations with damage effects and strain rate effects.

Declarations

Author contribution statement

Yunchen Suo: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
Ning Luo: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Haohao Zhang; Yabo Chai: Performed the experiments.
Weifu Sun; Cheng Zhai: Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data will be made available on request.
Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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