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Effect of fiber on early strength and interface stiffness of cemented tailings backfill

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Abstract

This paper studies the early mechanical properties of fiber-reinforced cemented tailings backfill (CTB) and discuss its modification mechanism. The effects of fiber types and addition (polypropylene fiber, basalt fiber and glass fiber) on unconfined compressive strength of CTB were studied by unconfined compressive strength test (UCS). Scanning electron microscopy (SEM) was used to investigate the microstructure of fiber-reinforced CTB. Based on the theory of interface mechanics and the contact mechanism of fiber interface, the evolution mechanism of fiber-reinforced CTB interface characteristic stiffness was further explored. The results show that the fiber type and content have a significant effect on the strength of CTB, and the optimum addition of fibers is 0.4%. The strength of fiber-reinforced CTB samples increased first and then decreased with the increase of fiber content. The stress of CTB sample without fibers reaches the maximum value when the strain is 1.01%, while introduction of basalt fiber increases that value to 3.74%. In addition, the microstructure characteristics show that the hydration products around the fiber make the CTB sample have better compactness, and fibers can effectively inhibit the crack development of the CTB samples. Finally, using the theory of interface mechanics, it is found that the interface stiffness of CTB sample with basalt fibers is the largest, but the interface contact stiffness increases first and then decreases with the increase of fiber content, which is consistent with the law of macroscopic strength change.

1. Introduction

Tailings are the abandoned residue of mining [1]. Accompanying with mining operation around the world, huge amounts of tailings are produced, which are mainly stored in tailings ponds is in China. According to statistics, there are more than 12,000 tailings ponds in China, and the storage capacity of tailings has reached 10 billion tons [2, 3]. However, the gravitational potential energy resulting from accumulated tailings makes the tailings pond huge threat to personal safety, housing property and ecological environment [4]. Therefore, the stability of tailings pond is still an outstanding problem to be overcome. Cemented tailings backfill (CTB) technology is an innovative tailings management technology and has been applied by mine managers and industry scholars around the world due to the economic and environmental benefits [5–9]. A large number of experimental studies have been conducted on the physical and mechanical properties of CTB. The unconfined compressive strength (UCS) is considered as the most important parameter in the backfill design of underground mines [10–13]. However, in the actual mining process, the drying shrinkage and dynamic disturbance, such as the extraction of adjacent stopes often induce cracks in the CTB structure [14, 15]. The common solution is to increase the content of hardener, which leads to a significant increase in backfill costs [16–18]. With the development of materials science, some scholars have found that adding fibers to mixtures can significantly improve the strength, toughness and crack resistance of test materials, thus effectively preventing crack propagation [19–21]. Mitchell and Stone first proposed a fiber reinforcement method for mine backfilling
design, which can significantly reduce the amount of cement used in backfilling and thereby reduces the cost of additives [22]. Yi et al found that fiber reinforced CTB stope may be much higher limits in dam height than that of non-fiber filled stope, but it depends on the degree of reinforcement [23]. Ma et al found that when the cement content was 10%, fiber significantly improved the toughness and peak strength of cement backfill [24].

The physical properties of the surfaces reflect the interaction between the microstructure components which directly affect the macrostructure stability of the reinforced tailings. In order to investigate the mechanism of the microscopic interfacial interaction between the fibers and the tailing sand, which variable affects the macroscopic compressive strength. In this paper, unconfined compressive strength and microstructure tests of CTB specimens reinforced by different fibers (polypropylene, glass fiber, basalt fiber) were carried out. The fiber content set as 0%, 0.1%, 0.25%, 0.4%, and 0.5%, respectively. The influence of type and content of fibers as well as the curing time on the strength and microstructure of CTB samples were discussed. The influence of fibers on the strength of CTB samples was verified by the interface mechanics theory. As a result, this study could provide theoretical support and technical reference for rational and effective utilization of fiber materials in mining engineering field.

Table 1. Chemical composition of tailings and cement.

| Varieties (%) | Fe₂O₃ | SiO₂ | Al₂O₃ | CaO | K₂O | MgO | CaCO₃ | MgCO₃ | Others |
|---------------|-------|------|-------|-----|-----|-----|-------|-------|--------|
| Tailings      | 26.3  | 48   | 7.3   | —   | —   | —   | 6.6   | 5.5   | 6.3    |
| Cement        | 3.11  | 20.34| 5.02  | 64.78| 0.35| 1.39| —     | —     | —      |

Figure 1. Frequency distribution curve of laser particle size of tailings.

Figure 2. Fiber types: (a) basalt fiber; (b) glass fiber; (c) polypropylene fiber.
2. Materials and methods

2.1. Materials

The tailings used in this experiment were selected from Tongnai iron tailings in Fuxin, Liaoning province. The dry density of tailings is 1.76 g cm\(^{-3}\), the porosity ratio is 0.862 and the natural water content is 14.1%. The chemical compositions were identified by x-ray fluorescence spectrometry (XRF). Tailings are mainly composed of SiO\(_2\) (48%), Fe\(_2\)O\(_3\) (26.3%), Al\(_2\)O\(_3\) (7.3%), CaCO\(_3\) (6.6%) and MgCO\(_3\) (5.5%). The particle size frequency distribution of tailings measured by laser particle size analyzer is shown in figure 1, and its average particle size is 0.075 mm. Ordinary Portland cement P.O.42.5 R was used as the binder and cement content was 10%. The main chemical compositions of tailings and cement are shown in table 1. As mixed water, tap water was used to mix tailing, cement, and fiber evenly [25]. The main elements in water are Ca (43.7 ppm), Mg (2.35 ppm), Na (3.10 ppm), and the PH value is ca. 7.35. Moreover, the fibers used to improve the mechanical properties of CTB samples in this study are shown in figure 2. The fibers have high stability in acid and alkali environments and a low absorption coefficient in water. The basic parameters and mechanical properties of fibers are shown in table 2.

2.2. Preparation and curing of sample

Cylinders with a diameter of 50 mm and a height of 100 mm were prepared for compressive strengths test. An electronic scale with accuracy of 0.01 g was used to weigh the materials for sample preparation. The ratio of cement to tailings (dry weight) was 1:9, fiber volume dosage was 0%, 0.1%, 0.25%, 0.4%, 0.5% 0%, 0.1%, 0.25%, 0.4% and 0.5%, and the addition amount of tap water was 14.1% of dry weight. The tailings, fibers, cement, and water are mixed in different proportions for 15 min [26], to obtain a homogeneous CTB mixture with the

Table 2. Basic parameters of fiber.

| Fiber type       | Polypropylene | Basalt      | Glass fiber |
|------------------|---------------|-------------|-------------|
| Length mm\(^{-1}\) | 15            | 15          | 15          |
| Average diameter \(\mu m\) | 18            | 13          | 8           |
| Density g cm\(^{-3}\) | 0.91          | 2.91        | 0.91        |
| Elasticity modulus /GPa | ≥3.5         | 100         | 4.29        |
| Tensile strength /MPa  | ≥458          | ≥4586       | 346.0       |
| Elongation/%          | ≥150          | 3.2         | 36.4        |
| Acid and alkali resistant | Well        | Excellent   | Better      |
desired consistency according to Chinese standard GB/T 50080-2016. Moreover, the fibers are added at the beginning of the mixing to avoid them floating. The prepared CTB samples were placed in a constant temperature curing box at 20 ± 5°C for 3 days and 7 days. In the unconfined compressive strength tests, 26 groups and 78 CTB samples in total were tested. These samples are varied in curing time, fiber types and fiber contents. The test scheme was shown in table 3. Capital 'J', 'X', 'B' and 'N' represent samples with polypropylene fibers, basalt fibers, glass fibers and without fibers respectively; '0.1', '0.25', '0.4' and '0.5' respectively represent the fiber content of the sample.

2.3. CTB sample test

2.3.1. Unconfined compressive strength test

After curing (3 and 7 days), CTB samples were subjected to a series of unconfined compressive strength (UCS) tests in accordance with ASTM C617-2010 [27]. UCS test adopts digital display pressure measuring instrument with maximum load capacity of 500 kN. All CTB samples were tested at a loading rate of 0.5 mm min⁻¹. The unconfined compressive strength test results were taken as the average value of CTB samples of three samples in each group. Figure 3 shows the unconfined compressive strength test device.

2.3.2. Scanning electron microscope test

After the unconfined compressive strength test, some samples were selected for microscopic test. In order to ensure photo quality, the impurities around the test block were blown by ear ball to facilitate observation of the connection between tailing sand and fiber. CTB samples with a thickness of 3–5 mm were soaked in anhydrous

| Test No. | Fiber type       | Fiber content | Curing days | Test No. | Fiber type       | Fiber content | Curing days |
|----------|-----------------|---------------|-------------|----------|-----------------|---------------|-------------|
| J-0.1    | Polypropylene fiber | 0.1           | 3           | J-0.1    | Polypropylene fiber | 0.1           | 7           |
| J-0.25   | Polypropylene fiber | 0.25          | 3           | J-0.25   | Polypropylene fiber | 0.25          | 7           |
| J-0.4    | Polypropylene fiber | 0.4           | 3           | J-0.4    | Polypropylene fiber | 0.4           | 7           |
| J-0.5    | Polypropylene    | 0.5           | 3           | J-0.5    | Polypropylene fiber | 0.5           | 7           |
| X-0.1    | Basalt fiber     | 0.1           | 3           | X-0.1    | Basalt fiber     | 0.1           | 7           |
| X-0.25   | Basalt fiber     | 0.25          | 3           | X-0.25   | Basalt fiber     | 0.25          | 7           |
| X-0.4    | Basalt fiber     | 0.4           | 3           | X-0.4    | Basalt fiber     | 0.4           | 7           |
| X-0.5    | Basalt fiber     | 0.5           | 3           | X-0.5    | Basalt fiber     | 0.5           | 7           |
| B-0.1    | Glass fiber      | 0.1           | 3           | B-0.1    | Glass fiber      | 0.1           | 7           |
| B-0.25   | Glass fiber      | 0.25          | 3           | B-0.25   | Glass fiber      | 0.25          | 7           |
| B-0.4    | Glass fiber      | 0.4           | 3           | B-0.4    | Glass fiber      | 0.4           | 7           |
| B-0.5    | Glass fiber      | 0.5           | 3           | B-0.5    | Glass fiber      | 0.5           | 7           |
| N        | —               | —             | 3           | N        | —               | —             | 7           |

Figure 4. Unconfined compressive strengths of CTB samples.
ethanol for 24 h followed by drying in a vacuum oven at 60 °C for 1–2 days. Then they were cast in epoxy resin and polished with sandpaper, using ethanol as lubricant. The final polishing is performed with a Monde paste of 1 μm diameter [28]. The SEM images are spliced together to reveal microstructural information.

3. Results and discussion

3.1. Effect of fiber on compressive strength of CTB specimen

Table 4 shows the unconfined compressive strength of CTB specimens after curing for 3 days and 7 days.

| Test no. | Compressive strength (3d)/MPa | Compressive strength (7d)/MPa |
|----------|-------------------------------|-------------------------------|
| J-0.1    | 0.687                         | 1.171                         |
| J-0.25   | 0.769                         | 1.326                         |
| J-0.4    | 0.890                         | 1.542                         |
| J-0.5    | 0.859                         | 1.471                         |
| B-0.1    | 0.732                         | 1.219                         |
| B-0.25   | 0.780                         | 1.347                         |
| B-0.4    | 0.923                         | 1.619                         |
| B-0.5    | 0.909                         | 1.568                         |
| X-0.1    | 0.748                         | 1.257                         |
| X-0.25   | 0.804                         | 1.467                         |
| X-0.4    | 0.968                         | 1.784                         |
| X-0.5    | 0.936                         | 1.700                         |
| N        | 0.732                         | 1.222                         |

The average compressive strengths of CTB samples are shown in figure 4. Compared with the CTB samples without fiber, the samples with fibers effect have higher UCS. For example, the UCS of J-0.4, X-0.4 and B-0.4 fiber reinforced samples at 3d is increased by 21.9%, 32.9% and 27.4%, respectively. Their 7d-UCS were 26.2%, 45.9% and 32.8% higher than that of the CTB samples without fibers. Therefore, fiber can improve the UCS strength of CTB samples.

As can be seen from the figure 5, with the increase of fiber content, the compressive strength of fiber-reinforced CTB first increases but then decreases afterward. The addition of fibers increases the internal friction force, and forms a mesh which, limits the lateral deformation of CTB, thus improving the integrity and stability of the tailings. This is the reason why the unconfined compressive strength is increased. Nevertheless, fibers have smooth surface and does not have the cohesive force [29]. When the fiber content beyond the limit value weak structure surfaces is produced in the CTB leading to the decrease in the unconfined compressive strength of the samples. Therefore, adding fibers into the tailings backfill mixture can improve the integrity of the matrix while the content of fibers should be controlled. Moreover, the compressive strength of the CTB samples cured for 7
days (with the fibers incorporation of 0.4%) was 1.54 MPa, 1.78 MPa, and 1.62 MPa, respectively. Basalt fibers increase the strength of CTB specimens better than polypropylene and glass fibers. This is because basalt fiber is an inorganic fiber of basalt ore, which has significant advantages over organic polypropylene and glass fibers in terms of elastic modulus, tensile strength, and affinity for the mineral cementitious matrix. Similar conclusions are also confirmed by Yan et al [30].

Figure 6. Stress-strain curves of three-day curing CTB: (a) polypropylene fiber; (b) basalt fiber; (c) glass fiber.

Figure 7. SEM of polypropylene fiber bunching.
3.2. Effect of fiber on stress-strain curve of CTB specimen

Figure 6 shows the stress-strain behavior of unreinforced and fiber-reinforced CTB specimens cured for 3 days. It is found that the peak strain of basalt fiber reinforced CTB samples increase first and then decrease with the increase of fiber content. Furthermore, the peak strains of polypropylene and glass fiber-reinforced CTB samples also improved with the increased fiber content within a certain range, these trends are so similar to the basalt fiber reinforcement. As shown in figures 6(a)–(c), the stress of CTB specimen without fiber reaches the peak value when the strain is 1.01%. When 0.4% fiber (polypropylene fiber, basalt fiber, glass fiber) was added, the strain of CTB specimen reached the peak value at 2.14%, 3.74%, and 3.21%, respectively. It can be seen that adding fiber into the tailings filling mixture can improve the peak compressive strength of CTB samples and transform the brittle failure into the ductile failure. With the increase of stress, the fiber-reinforced CTB samples present strain hardening properties. This phenomenon shows that the strength of the specimen increases under higher strain due to fiber stretching. While Cao et al. [26] concluded that the supplementary contribution of the tensile strength of fibers at higher strain values also could well explain this phenomenon. Moreover, the performance of the CTB specimens with basalt fibers was significantly better than that of the glass and polypropylene fibers. This is due to the change in peak strain caused by the different strength increases of the CTB specimens with the different fibers, which in comparison shows that the basalt fibers have better improved the strength and stiffness of the CTB specimens [30].

![Figure 8: Effect of curing time on CTB stress-strain curve.](image)

![Figure 9: Effect of curing time on stress-strain curve of basalt fiber (0.4%) CTB.](image)
As can be seen from figure 7, the probability of fiber-fiber contact is greatly increased at higher fiber content in CTB samples incorporated with polypropylene fibers, which are more likely to produce agglomeration compared to basalt and glass fibers. The friction between the fiber interfaces is negligible, forming a weak bonding surface and resulting in insignificant strength increases in the CTB specimens (as shown in figure 4). While Yan et al [30]. Also indicates that the addition of polypropylene fibers barely modifies the compressive strength which may be attributed to the dispersion of polypropylene fibers that sometimes forms agglomerates providing a clear initiation site for micro-crack generation. This conclusion is also consistent with the results of previous studies [31–33].

### 3.3. Effect of curing time on CTB sample

Some studies point out that the mechanical properties of CTB materials are enhanced with the extension of curing time, which is mainly caused by the ongoing cement hydration [34–36]. Figure 8 and 9 show the stress-strain relationship of CTB samples and CTB samples reinforced by basalt fiber (0.4%) after curing for 3 and 7 days respectively. It was observed that the strength of fiber-free CTB cured increased from 732kPa to 1222kPa at 7 days, with an increase of 66.9%. Similarly, the peak strength of the basalt fiber reinforced sample increases from 968kPa to 1784kPa at 7 days, With an increase of 84.3%. However, the peak strain of the sample without
fiber decreases from 1.01% on day 3 to 0.751% on day 7, and the peak strain of fiber-reinforced sample (X-0.4)
decreases from 3.74% on day 3 to 2.78% on day 7. Therefore, it can be seen that curing time improves the
strength of CTB samples. This is because the hydration degree of CTB sample in 7 days is greater than that in 3
days. After hydration, the brittleness of CTB sample increases, resulting in the decrease in the peak strain in 7
days. The strength of the fiber reinforced sample is obviously better than that of the unreinforced sample and can
bear more pressure. CTB samples with different reinforced fibers have brittle failure after reaching peak
strength, and the samples suddenly collapse and fail, as shown in figure 10.

3.4. SEM analysis of CTB samples

Figure 11 shows the microstructure morphology of fiber reinforced CTB sample. As can be seen from figure 11,
fibers were pulled out after UCS tests, but the fibers were intact. As shown in figure 11(c), cement hydration
products (C-S-H) are filled in voids between the fiber and tailing sand and thereby reduces the porosity of the
CTB, making it more compact. In addition, as shown in figure 11(b), some fibers are almost completely covered
by hydration products. Due to the bond between fiber and mortar, when cracks are formed under the stress of
the sample, the fibers at both ends of the cracks play a bridging role. Therefore, when the sample is under
pressure, the fiber can share certain tensile stress and transfer the concentrated stress to both ends of the crack,
which reduces the interface slip and improves the interface bond strength, thus limiting the lateral deformation
of tailing sand and improving the overall stability of the sample [26, 37, 38].

According to the basic fiber parameters table 3, the tensile strength of polypropylene fiber, basalt fiber and
glass fiber is 458 MPa, 4586 MPa and 346 MPa respectively. The force produces by the crack is not enough to
break the fiber, so the fiber can not only effectively restrain the development and propagation of cracks, but also
bridge the crack and prevent the secondary diffusion of cracks.

3.5. CTB interface effect analysis

When two objects contact each other, the interface will be deformed under the action of load. Under the same
load, the contact interface with different properties and shapes is also very different. In order to measure the
deforamtion, the concept of contact stiffness is introduced in this paper. Contact stiffness is the normal stiffness
defined as:

$$K = \lim_{\Delta\delta \to 0} \frac{\Delta W}{\Delta\delta}$$

Where, $K$ is the contact stiffness, $W$ is the normal load, and $\delta$ is the interface normal deformation.

It is assumed that the fiber surface is smooth. The tailings particles can be regarded as spherical particles. The
fiber is deformed after extrusion and, thus the surface of fiber can be regarded as a concave plane. When the
interface between fiber and tailings particles is subjected to external force, the fiber first compresses and deforms,
absorbing part of the energy. When the fiber deformation reaches a limit, the contact interface between fiber and
tailings particles would transform into a sphere and a curved surface in a two-dimensional plane. The fiber
reinforced interface can be simplified into the contact between tailings particles (contact between two spheres).
and the contact between particles and fibers (contact between spheres and surfaces). The unreinforced interface
can be simplified into the contact between tailings particles, as shown in figure 12.

When two spheres contact each other, the contact interface can be considered as a plane, and the
corresponding pressure distribution is the Hertz distribution \[ p = \frac{4F}{\pi R^2}. \]
Using Hertz contact theory, the relation
between load and deformation can be expressed as follows:

\[ W = \frac{2E\sqrt{R}\delta^{3/2}}{3} \]

Where, \( W \) is the normal load; \( E \) is the comprehensive contact modulus of the two bodies, and
\[ \frac{1}{R} = \frac{1}{2}\left(\frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2}\right). \]

Where \( E_1 \) and \( E_2 \) are the elastic moduli of the two objects respectively, \( v_1 \) and \( v_2 \) are
Poisson’s ratios of two materials respectively, \( R \) is the combined radius of curvature of two objects, and
\( 1/R = (1/R_1 + 1/R_2) \), \( R_1 \) and \( R_2 \) are the radius of curvature of the two spheres respectively. \( \delta \) is the normal
approximation or total deformation of the centers of the two bodies.

According to the definition of contact stiffness, the derivative of equation (2) can be obtained:

\[ K = \frac{dW}{d\delta} = E\sqrt{R}\delta \]

Substitute Formula (2) into Formula (3) to obtain:

\[ K = \sqrt{\frac{3E^2RW}{2}} \]

Even though the interface of a sphere and curved surface is not planar, but the relationship between deformation
and stress still obeys Hertz contact theory \[ \langle 40 \rangle \], as shown in figure 12. Therefore, the relationship between load
and deformation is still as follows:

\[ W^* = \frac{2E\sqrt{R}\delta^{3/2}}{3} \]

Where \( 1/R^* = 1/R_1 - 1/R_2^* \), \( R_1 \) and \( R_2^* \) are the curvature radius of tailing sphere and the curvature radius of
fiber concave surface respectively.

Similarly, after derivation, the equation can be rewritten as:

\[ K^* = \sqrt{\frac{3E^2R^*W}{2}} \]

As shown in table 5, the fiber bending angles of 45°, 90° and 135° are selected for analysis. The interface
stiffness has the highest value when the bending angle is 45°, and it decreases with the increasing bending angle
of the fibers. When the angle reaches 135°, the interface stiffness of CTB samples is higher than that of fiber-
reinforced ones. But in fiber-reinforced CTB samples, the bending angle of fibers can hardly reach 135°. When
the radius of composite curvature is constant, the composite modulus and normal load of basalt fiber are better
than those of glass fiber and polypropylene fiber, so the interface stiffness of basalt fiber is better than that of g
the other two fibers. This is reason why the UCS of fiber-reinforced CTB samples is greater than that of pure CTB
samples, and the UCS of the CTB samples was ranked as X > B > J > N, indicating that the basalt fibers
worked best among the three selected fibers.

According to formulas (4) and (6), the interface stiffness \( K \) is proportional to the 1/3 power of the normal
load \( E \). As the UCS value of CTB samples increases first and then decreases with the increase of fiber content, the
interface contact stiffness also increases first and then correspondingly. However, in general, the fiber-reinforced
CTB samples have higher interface stiffness and as such are more stable than the CTB samples without fibers.

Table 5. Fiber stiffness parameter.

| Fiber type       | Combined radius of curvature/mm | Composite modulus/MPa | Normal load/MPa | Interface stiffness/MPa |
|------------------|---------------------------------|-----------------------|-----------------|------------------------|
|                  | 45°    | 90°    | 135°   | 45°    | 90°    | 135°   | 45°    | 90°    | 135°   |
| Polypropylene    | 0.0753 | 0.0756 | 0.0759 | 1.712  | 0.903  | 0.669  | 0.302  | 0.066  |
| Basalt fiber     | 0.0753 | 0.0756 | 0.0759 | 1.722  | 1.060  | 0.708  | 0.356  | 0.087  |
| Glass fiber      | 0.0753 | 0.0756 | 0.0759 | 1.712  | 1.000  | 0.692  | 0.335  | 0.078  |
| No fiber         | 0.0038 | 0.0038 | 0.0038 | 0.739  | 0.732  | 0.131  | 0.131  | 0.131  |
4. Conclusions

In this paper, the mechanism of interaction between fiber particles is studied by UCS test and SEM, and the following conclusions are drawn based on the analysis of interface mechanics:

(1) The UCS and peak strain of the fiber reinforced CTB sample increase first and then decrease with the increase of fiber content. Among the fibers, basalt fiber is obviously superior to others (polypropylene and glass fiber), and the optimal fiber content is 0.4%.

(2) UCS of CTB samples increases with curing time. UCS value of fiber-free CTB samples increases from 732 kPa at 3 days to 1222 kPa at 7 days. For CTB samples reinforced by basalt fibers with the content of 0.4%, the UCS increases from 968 kPa at 3 days to 1784 kPa at 7 days. Addition of both glass fiber and polypropylene fibers also increases the UCS of CTB samples to varying degrees.

(3) Morphology analysis shows that the hydration products are around the fibers. It not only improves the strength of fiber itself, but also increases the compactness of samples. In addition, compared with the samples without fibers, fibers can effectively prevent the secondary crack propagation.

(4) The stiffness of basalt-fiber-reinforced interface, glass-fiber-reinforced interface, polypropylene-fiber-reinforced interface and the non-fiber-reinforced interface decreases in sequence. The interface stiffness of CTB specimens increases with the increase of normal load, but it increases first and then decreases with the increase of fiber content.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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