Research Paper

Fibre-Reinforced Grout for Micropile Construction

Maged Abdirlahem¹* and M. Hesham El Naggar²

Abstract: Hollow bar micropiles (HBMP) are increasingly used to support heavy structures owing to their ability to carry considerable axial loads. However, their lateral capacity is relatively small due to their small flexural strength, which could limit their application for structures subjected to large lateral loads. Enhancing the micropile flexural strength by utilizing fibre-reinforced grout in its construction can thus improve its lateral performance. This study investigates the use of four types of fibers in grout mixture with different dosages to enhance the strength of grout used for micropile construction. Plastic, basalt, steel and micro-steel fibers were applied with dosages of 1%, 1.5% and 2%. Based on the obtained results, steel fibers were selected for further investigation. Nine model micropiles 1000 mm long and 76 mm in diameter were casted and tested in a laboratory environment with two different types of steel fibers. The micropiles were subjected to pure bending tests and the moment – curvature curves were extracted. The moment – curvature results indicated that the micropiles moment capacity increased and their post-cracking behaviour improved by adding steel fibers to the grout mix. As part of a large-scale study of lateral performance of single and grouped micropiles installed in cohesionless soil, one micropile was constructed with 1% micro-steel fiber to investigate its effect on its lateral performance. The lateral load test results indicated that the lateral capacity of the reinforced micropile improved by 10% over that of the non-reinforced micropile.

Keywords: hollow bar micropiles, grout, fiber, moment-curvature, lateral capacity

Introduction

In recent years, micropile technology is being used extensively for both retrofitting existing foundations and supporting new structures. Micropiles can carry considerable axial loads, but their lateral capacity is relatively small when compared to other type of piles due to their small cross-sectional area. This hinders their application to support structures subjected to relatively large lateral loads. Due to their advantages related to constructability, ground improvement effects, and efficient load transfer mechanism, micropiles are increasingly employed to support heavy structures. In current practice, steel casings are used along the upper part of the micropile to increase its lateral resistance. However, this increases its cost and construction time. In addition, Turan et al. (2008) showed that, for micro-piles subject to lateral harmonic loading, bending moments in the pile increase significantly just below where the casing terminates (i.e. in the uncased portion of the pile) as a sudden decrease in the flexural strength of micropiles could attract more dynamic loads. Alternatively, adding reinforcing fibers to the grout can enhance the lateral performance of micropiles by increasing the flexural strength and post-cracking behaviour.

The Federal Highway Administration (FHWA, 2015) recommended four different methods to improve the lateral capacity of micropiles. Similarly, Wolosick and Scott (2017) illustrated the need for reconsidering battered micropiles when large lateral loads are anticipated. They advised that when lateral loads on micropiles are anticipated, a steel pipe section with a length equal to 20-25 times the drill-hole diameter should be used in the upper portion of the pile. Enhancing the flexural strength of the grout, which is one of the main micropile materials, could be an efficient alternative. Adding short discontinuous reinforcing fibers to the grout mixture could improve its mechanical properties. Steel-fiber reinforced concrete started to find its way into many structural applications, especially when the structure is subjected to loads over the serviceability limit in bending and shear (Bencardino et al., 2008). Thomas and Rasmussen (2007) reported experimental results and developed an analytical model to evaluate the influence of fibers on the mechanical properties of concrete. They concluded that fibers can improve the mechanical properties significantly. It is common in North America to use neat grout which is a mix of cement and water. However, sand is added in some parts of the world
the influence of steel fibers on the flexural strength of micropiles. In the third stage, the derived moment-curvature curves were implemented in LPile (Isenhower, et al., 2017) software to evaluate the lateral capacity of micropiles. The fourth stage was a part of a large study on the single and group performance of micropiles installed in cohesionless soil. A micropile, denoted MP6, was constructed with 1% micro-steel fibers to investigate the effect of fibers on the lateral performance of a full-scale micropile. The stiffness and capacity of MP6 were compared with those obtained for other micropiles installed in the same environment but with conventional grout.

**Laboratory Testing Program**

This section presents and discusses the laboratory testing program. The laboratory testing program consisted of two main components: evaluating the mechanical properties of fiber reinforced grout (compressive strength, tensile strength, elastic modulus of elasticity, and flexural strength) and conducting pure bending moment tests of micropile models.

**Mechanical properties of fiber-reinforced grout**

The mechanical properties of reinforced grouts were investigated by casting specimens with four different types of fibers and three different volume dosages for each type.

Two hundred and thirty-four cylinders with a diameter of 100 mm and length of 200 mm were cast and tested to evaluate the compressive strength, tensile strength, and modulus of elasticity. The numbers of performed tests for each type of fibers is summarized in Table 2. Cylindrical reinforced grout specimens were selected to enable casting the reinforced grout along the vertical direction to account for the orientation of the fibers in relation to the applied load. The compressive strength was determined according to ASTM C39 and the tensile strength was obtained in accordance to ASTM C496. In addition, six cylinders were cast for controlled specimens with no fibers. Six cylinders for each volume content of different fiber dosage were evaluated for static modulus of elasticity and tested according to ASTM C469. To evaluate the effect of fibers dosage on the flexural strength, seventy-eight beams with dimensions 100 mm by 100 mm by 380 mm were cast. Six beams for each type of fibers with different dosages were cast and tested under Third-Point loading in a flexural testing machine to evaluate the effect of fibers on the flexural strength of different mixtures. The Third-Point Loading was performed in accordance to ASTM C1609.

The mixing procedure was performed as follows: the required quantity of water was added to the cement and mixed for about four minutes, then fibers were sprinkled gradual-

<table>
<thead>
<tr>
<th>Type of Fiber</th>
<th>L (mm)</th>
<th>D (mm)</th>
<th>Aspect Ratio</th>
<th>Unit Weight kN/m³</th>
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<td>0.2</td>
<td>60</td>
<td>78.5</td>
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<tr>
<td>Steel Fiber</td>
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<td>0.55</td>
<td>60</td>
<td>78.5</td>
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<tr>
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<td>30.8</td>
<td>18</td>
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<tr>
<td>Plastic Fiber (Fibermesh 650)</td>
<td>Graded</td>
<td>Graded</td>
<td>96.5</td>
<td>9.1</td>
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</table>


Fiber-reinforced grout can control crack initiation and subsequent crack development. Extensive research efforts were focused on the behavior of the fiber reinforced concrete (Mansur et al., 1999). However, adding fibers to the grout used in micropile construction to enhance its capacity has not been investigated. Micropiles are characterized as long flexible piles because of their high slenderness ratio. Usually when long flexible piles are subjected to lateral loads, the failure occurs within the micropile material (i.e. grout) rather than in the surrounding soil. Thus, enhancing the grout flexural strength can improve the micropile lateral resistance.

The aim of this study is to investigate the mechanical properties of fiber reinforced grout for potential use in micropile applications. The study was divided into four main stages. In the first stage, four different fiber types were selected: plastic fibers (PF), basalt fibers (BF), micro-steel fibers (MSF) and steel fibers (SF), and the mechanical properties of the composite material were evaluated. Figure 1 shows the four types of fibers used in this study. The properties of the four different types of fibers employed in this study are illustrated in Table 1. Cylindrical specimens were tested for plain grout and grouts reinforced with different types and dosages of fibers for tensile capacity, compressive capacity, and modulus of elasticity. Beams were also cast and tested under flexural loading conditions. Based on the obtained results from the first stage and the constructability of the fiber-reinforced grout, steel fibers were selected for further investigation. In the second stage, the flexural strength of scaled micropile models was investigated. Models of micropiles were cast with two different steel fibers and tested under pure bending. Deflection along the micropiles was measured using LVDT’s, and the moment-curvature was derived for each model to evaluate the influence of steel fibers on the flexural strength of micropiles. In the third stage, the derived moment-curvature curves were implemented in LPile (Isenhower, et al., 2017) software to evaluate the lateral capacity of micropiles. The fourth stage was a part of a large study on the single and group performance of micropiles installed in cohesionless soil. A micropile, denoted MP6, was constructed with 1% micro-steel fibers to investigate the effect of fibers on the lateral performance of a full-scale micropile. The stiffness and capacity of MP6 were compared with those obtained for other micropiles installed in the same environment but with conventional grout.

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The mixing procedure was performed as follows: the required quantity of water was added to the cement and mixed for about four minutes, then fibers were sprinkled gradual-
ly by hand while continuously mixing for an additional four minutes. Mixtures were prepared using a small mixer in the lab to ensure proper consistency was achieved. The mixtures were poured in 100 mm diameter by 200 mm length cylindrical molds and 100 mm by 100 mm by 380 mm beams. All specimens were de-moulded after 24 hours then placed in a control room with a relative humidity of 100% and a constant temperature of 23°C.

According to FHWA (2015), the water to cement (w/c) ratio for micropile application should be between 0.4 to 0.5 by weight unless admixtures are used. In the current study, Portland cement Type 10 and w/c ratio of 0.45 were used.

**Pure bending tests**

Based on the results obtained from the first stage, two types of fibers with 1% dosages of volume were selected for this stage to evaluate the effect of adding fibers on the bending moment capacity of micropiles. Nine model micropiles were cast: three with neat grout without fibers, three with 1% of steel fiber, and three with 1% of micro-steel fiber. The model micropile was 1000 mm long and had a diameter of 76 mm. The threaded hollow steel bar (R38N/21) used to construct the models had an outer diameter of 38 mm and inner diameter of 22 mm. The ultimate tensile load of the hollow bar was 500 kN and thread type was ISO 10208. The neat grout (cement + water) was mixed with a 0.45 w/c ratio. The w/c was selected as per the recommendations of FHWA for micropile application. All micropiles models were de-moulded after 24 hours and kept in a controlled room with a relative humidity of 100% and constant temperature of 23°C. The models were left for 28 days in the controlled room before testing. The model micropile was loaded with concentrated loads at the one third and two thirds of its total length to produce a pure bending moment at the middle third of the micropile. Four LVDT’s were utilized to measure the deflection along the micropile length. The load was applied in very slow fashion using a 100 kN hydraulic jack with a maximum stroke of 152.4 mm. The applied load was measured using a load cell with a capacity of 100 kN. All the LVDT’s and the load cell were connected to a data acquisition system which collected the data at a sampling rate of one reading per second. To facilitate applying the load on a curved surface, a special piece of solid steel was designed with the same micropile outer diameter. The load test setup is shown in Figure 2.

Micropiles were subjected to pure bending tests and their deflections were measured along the micropile length via the LVDTs. A quadratic function was utilized for curve fitting the measured deflections at measuring points to establish a continuous deflection curve along the micropile, which was then double differentiated to develop the curvature profile. The moment-curvature diagram was then obtained by plotting the applied moment vs. the developed curvature at each load increment. The cracking behaviour was monitored during the tests and the results were reported.

**Laboratory Testing Program Results**

**Mechanical properties of fiber-reinforced grout**

This section presents the results obtained from the experimental program including the compressive strength, tensile strength, elastic modulus of elasticity, and flexural strength.

**Compressive and tensile strengths**

The average compressive strength for neat grout was 42 MPa, which is higher than the specified limit by FHWA (2015) of 30 to 35 MPa for micropile applications (Littlejohn and Bruce, 1977). The results of the compressive strength are presented in Figure 3(a). The compressive strength of MSF and SF mixtures increased as the volume content of the fibers increased from 1% to 2%. For BF mixtures, the compressive strength increased slightly with the increase of the volume content while the compressive strength of the PF mixtures decreased as the volume content of the fibers increased from 1% to 2%. For BF mixtures, the compressive strength decreased by about 20% and 34% for 1% and 2% dosage. The decrease in compressive strength as the fiber dosage increased is attributed to a decrease in the cement content of the mixture and stress concentrations around softer plastic fibers. The PF replaced a percentage of the cement in the mixture which was not fully compensated by the additional strength due to the fibers themselves. On
the other hand, the compressive strength for MSF mixtures increased by up to 16% with the increase in volume content of the fibers.

The tensile strength of the MSF and SF mixtures increased significantly with increasing dosages up to 2% as presented in Figure 3(b). It increased by more than 100% when compared to neat grout mixtures. The tensile strength of the PF mixtures increased by about 20% when the dosage increased to 2% of volume content, while the BF mixture with 2% dosage demonstrated an increase in the tensile strength by about 30% compared to neat grout. The tensile strength of MSF mixtures increased dramatically, compared to the increase in its compressive strength.

Elastic modulus
The average measured static elastic modulus of neat grout was for six cylinders was 13.5 GPa. It was calculated based on ASTM C469/C469M for stress corresponding to a strain of 50 millionths, MPa. For design purposes, FHWA 2015 recommended estimating the grout elastic modulus by:

$$E_{\text{grout}} = 4732 \sqrt{f'_c}$$

(1)

where $E_{\text{grout}}$ is the modulus of elasticity of grout (MPa). $f'_c$ is the compressive strength of the grout (MPa).

However, Equation 1 was proposed for concrete (ACI code 318-08) and not for neat grout. Thus, it overestimates the elastic modulus for neat grout. The calculated $E_{\text{grout}}$ based on Equation 1 was 31 GPa, which is higher than the value obtained from the test results. Dhbe (2013) and Aboutabikh (2016) measured the static elastic modulus of neat grout and reported its value to be about 15 GPa, which is in good agreement with the test results. Therefore, Equation 1 should be modified to estimate the static elastic modulus of neat grout, i.e.:

$$E_{\text{grout}} = 2200 \sqrt{f'_c}$$

(2)

For 1% dosage, the plastic fibers resulted in the highest percentage increase among the four types of fibers considered. However, slight improvement was observed as dosage increased to 2%. However, the elastic modulus for micro-steel fiber, steel fiber and basalt fiber mixtures increased linearly with the fiber dosage, with micro-steel fibers mixture resulting in the highest elastic modulus of fibers tested.

Flexural strength
To assess the flexural strength of different mixtures, six beams were cast and tested after 7 and 28 days. Four different percentages of fiber dosage were used for each type of fiber except for basalt fiber where only 1 and 2% were used. All tests were carried out according to ASTM C78. Figure 4(b) summarizes the test results of the different mixtures with different fiber dosages. The flexural strength varied between 10 and 20% of the corresponding compressive strength, which agrees with US Army Corps of Engineers (1984) recommendations that the flexural strength should be between 10-20% of the compressive strength. The flexural strength of the micro-steel fiber mixture with 2% of volume content was about 23% of its compressive strength. The micro-steel fiber mixtures showed a dramatic increase in the flexural strength by about 153% for a 2% dosage. Plastic fiber mixtures with 1% dosage exhibited slight decreases in flexural strength, while a 2% dosage showed an increase by about 28%. The flexural strength of basalt fiber mixtures increased by 56% for 1% dosage and increased slightly as fiber dosage increased from 1 to 2%.

Pure bending tests
Figure 5 presents the moment-curvature curves for the nine model micropiles. As shown in Figure 5, the moment capacity of the un-reinforced micropiles compared to those with steel fibers. The moment – curvature curves indicated that the moment capacity of micropiles increased and the post-cracking behaviour improved by adding steel fibers to the grout mix. The bending moment capacity of the micropiles increased significantly as a result of adding 1% by
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Figure 4. (a) Modulus of elasticity; (b) Flexural strength for four types of fibers with different dosages

Figure 5. Moment-curvature curves obtained from pure moment tests

volume of steel fibers. In addition, micropiles with no steel fibers exhibited brittle failure while the micropiles with steel fibers displayed ductile behaviour. Figure 6 shows the post cracking behaviour of micropiles cast with and without reinforced grout. The micropiles with steel fibers exhibited improved performance even at large deflections and the grout remained in contact with the central hollow bar. On the other hand, un-reinforced micropiles exhibited brittle failure and the grout crushed and separated from the central hollow bar.
Full-Scale Test

A full-scale fibre-reinforced micropile (designated MP6) was constructed as part of a large study to investigate the performance of micropiles installed in cohesionless soil. Micro-steel fibers were added at dosage of 1% by volume to the neat grout mix, which had a w/c ratio of 0.45. The micro-steel fibers were added manually to the top 2.25 m (about 15 times the micropile diameter) of the 6.0 m long micropile. The micro-steel fibers were sprinkled gradually by hand while the drilling machine introducing the competent grout to the hole. All health and safety measures such as wearing gloves, masks and eye contact with the driller were taken during the drilling and introducing the micro-steel fibers. The micropile was installed with a drill bit diameter of 152 mm, and the hollow bar was R51N (51 mm outer diameter and 33 mm inner diameter). The final grout had a specific gravity of 1.64 and a minimum compressive strength of 40 MPa and the average split tensile strength was 3.97 MPa. The cylinders were tested after 28 days to determine the grout compressive strength after 28 days was 40 MPa and the average split tensile strength was 3.97 MPa. The results obtained for the compressive strength met the minimum requirement set by FHWA (2013) for compressive strength of grout after 28 days.

Loading setup and pile instrumentation

A test setup was designed and manufactured to facilitate applying monotonic lateral loads on the micropile head as shown in Figure 10. A reaction frame was used to support the loading system, which consisted of a steel rod threaded to the load cell from one end and attached to a steel plate. The Hydraulic jack was bearing against two steel plates, the two steel plates were connected with two steel bars secured by four hex nuts so the load can transfer to the pile head. The loading frame was connected to the micropile head using a hinged connection to apply the lateral load with zero moment. A square steel plate (250 × 250 × 30 mm) with a hex nut (ID 51 mm) welded to one side was threaded to the hollow bar head to facilitate applying the lateral loads. The load was applied through a hollow cylinder hydraulic jack with a capacity of 900 kN and recorded via a 900 kN load cell. Four HLP190 (hybrid Linear Potentiometers) were attached to the steel plate in a square arrangement to measure the micropile lateral deflection. The load cell and the LVDT’s were connected to a data logger to obtain the readings every one second. MP6 was equipped with eight foil strain gauges concentrated on the top 2.5 m of the pile where large deflection and bending moment were expected. The foil strain gauges (SG) were installed in control lab environment with the following sequences:

Site description

The test site is located near Ayr, Ontario. In-situ and laboratory tests were conducted to characterize the soil profile and obtain the soil shear strength parameters. Three boreholes were drilled and standard penetration tests (SPT) were conducted. Soil samples were extracted using the spilt spoon method for laboratory testing. Additionally, four piezocone penetration tests (CPT) were performed across the site, two of them were in the vicinity of the test locations (CPT1 and CPT2).

Figure 7 shows the SPT results for the closest boreholes to the test location (BH1 and BH2). Seams of silt and silty clay were observed during drilling of borehole 1 at different levels of the borehole. The ground water table was observed at 9.5 to 10.5m below ground surface. Figure 8 shows CPT sounding, which indicates the soil was mainly sand with some seams of silt and sandy silt according to the soil behaviour type proposed by Robertson (1990). The average cone resistance corrected for the pore water pressure (q) ranged from 10 to 30 MPa in the upper 6.5m and 30 to 45 MPa from 6.5m to 8m and an average of 20 MPa below that. The relative density Dr was obtained using the correlations proposed by Kulhawy and Mayne (1990) based on SPT and CPT data and are plotted along the depth in Figure 9a. The angle of internal friction was evaluated from direct shear tests and from two different correlations proposed by the American Petroleum Institute (1987) and Kulhawy and Mayne (1990). The calculated angle of internal friction profiles was compared with the direct shear test results in Figure 9b. As can be noted from Figure 9b, there is a good agreement between the computed values of the angle of internal friction using the two correlations with the measured values obtained from direct shear tests. Based on the collected data, the average value of peak angle of internal friction is approximately 42°. The sieve analysis showed that the soil along the piles is primarily fine sand as seen in Figure 9c.

Figure 6. Post cracking behaviour of fiber reinforced and non-reinforced grouted micropiles
Figure 7. BH1 and BH2 with SPT N values and water content

Figure 8. CPT sounding for CPT1 with SBT
Figure 9. Properties of soil: a) relative density; b) angle of internal friction; and c) grain size distribution
Grind the steel bar surface using coarse sanding disc to flat the surface then grinding with a fine sanding to smooth the surface.

Clean the surface using acetone and sponges before installing the SG.

Mark the SG location and position the SG on the steel bar.

Attach the SG to the steel bar surface. Use the tape to handle the SG and avoid touching the SG.

Peal partially the tape and apply adhesive to avoid air bubbles and provide excellent attachment. Push a thumb on the tape and maintain a thumb pressure for 1.5 minutes.

After the adhesive dry carefully remove the tape from the SG.

Inspect the SG making sure no bubbles and no difference in colors.

Apply coating to the SG for waterproofing and mechanical protection.

Check the electrical resistance of the SG.

Label the SG and record the gauge factor.

Micropile MP6 was loaded monotonically in equal increments of 3 kN, with each increment being maintained for 5 minutes.

**Full-scale lateral test results**

The load - deflection curves for micropile (MP6) installed with reinforced grout (1% of MSF) and micropiles installed with just neat grout containing no fibers (MP1, MP2 and MP5) are shown in Figure 11. The results of micropiles MP1, MP2 and MP5 are reported elsewhere (Abdlrahem and El Naggar, 2021). MP6 showed a stiffer lateral response when compared to the other three micropiles. The micropile lateral capacity is considered as the lateral corresponding to 25 mm lateral deflection at the micropile head. The lateral capacity of the fiber reinforced pile increased by 10% compared to the average capacity of the three micropiles installed with no fiber.

**Numerical Modeling**

LPile is a special purpose program used to analyze the response of piles under lateral loading. The program utilizes the $p-y$ curve method for analyzing the nonlinear lateral load transfer of piles. Lateral deflection, bending moment, shear force, and soil response over the pile length can be computed using the LPile program. The program uses various types of published and well documented lateral load-transfer curves ($p-y$ curves) to model different types of soils (Isenhower et al., 2017). LPile offers the option to incorporate the bending moment versus bending curvature in the analysis when they are available. The nonlinearity of soil-pile systems is caused by two main factors: the nonlinear response of soil to lateral loading; and the nonlin-
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Figure 13. Bending moment along the depth of the three micropiles using Reese model

Figure 14. Maximum bending moment versus maximum head deflection curves for three micropiles

The mechanical properties of neat grout and various fiber-reinforced grouts were investigated in this study by performing several laboratory tests for compressive strength, tensile
strength, elastic modulus, and flexural strength. Furthermore, model micropiles with 1000 mm length and 76 mm diameter were cast and subjected to pure bending moment tests in controlled environment to investigate the effect of adding fibers on the bending moment capacity of micropiles. In addition, a numerical model was developed utilizing the moment-curvature curves obtained from the pure bending moment tests and the results were reported. The optimum dosage of fibers was selected based on the laboratory study and used to construct a full-scale micropile 6 m long and 172 mm in diameter in cohesionless soil. The micropile was tested under monotonic lateral loading. Based on the obtained results from this study, the following conclusions can be made:

- The compressive strength of plastic fiber mixtures decreased slightly but the tensile strength increased as the fiber dosage increased.
- The compressive and tensile strengths of micro-steel fiber and steel fiber mixtures increased with the fibers dosage. The compressive strength increased by 21% for both fibers mixtures while the tensile strength increased by 110% and 100% for grout mixed with micro-steel fibers and steel fibers, respectively.
- The micro-steel fiber mixtures at 2% dosage exhibited the highest elastic modulus and flexural strength.
- The flexural strength of mixtures with 2% dosage of basalt fiber increased by 56%.
- The bending moment capacity of micropiles increased and the post-cracking behaviour improved by adding micro-steel fibers and steel fibers to the grout mix.
- Micropiles cast with steel fibers showed greater ductility (i.e. greater energy absorption). On the other hand, micropiles cast with un-reinforced grout exhibited brittle failure and the grout separated from the central hollow bar in fashion.
- The maximum bending moment developed at a depth equal to 7.1 d and 8.7 d for micropiles constructed with un-reinforced and fiber-reinforced grouts, respectively.
- The lateral capacity of full-scale micropiles constructed with fiber-reinforced grout increased by 10% compared to the average capacities of the three micropiles constructed with un-reinforced grout.

Data Availability
Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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