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Effect of Spatial Variability on Compressive Strength of MICP-treated Soils

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ABSTRACT

Spatial variability has been identified as a major cause of uncertainties in determining the geotechnical properties of chemically and biologically treated soils. This can be attributed to the fact that in natural conditions, the grain and pore size distribution of soils exhibit sporadic spatial variation. This spatial variability, along with other factors, contributes to an uneven distribution of the stabilizing agents, resulting in further spatial variability in other properties of treated soils such as their strength. This paper aims to identify the extent to which spatial variability affects the strength of cylindrical soil samples that have been treated by the Microbially Induced Calcite Precipitation Method (MICP). A random finite volume method (RFVM) analysis was performed to simulate stress-strain behavior and the strength of MICP-treated soil samples to achieve this goal. In this RFVM model, the spatial variability in both the amount (percent by weight) and the extent (maximum precipitation distance from injection port) of precipitated calcite were considered. The results confirmed the adverse effects of both types of spatial variability on the stress-strain behavior and the peak (yield) stress of the treated samples. The results also showed that spatial variability in the extent of precipitated calcite plays a more significant role in the behavior of treated soils.

INTRODUCTION

Microbially Induced Calcite Precipitation (MICP) is a biochemical process that utilizes microbial metabolic reactions byproducts to precipitate traces of calcium carbonate ($CaCO_3$) within a soil medium (Dejong et al., 2015; Hall et al., 2023; Khodadadi Tirkolaei et al., 2020; O'Donnell et al., 2019). The precipitated calcium carbonate improves the soil's mechanical and engineering properties such as erosion resistance, strength, and stiffness(Fu et al., 2023; Lai et al., 2023; Liu et al., 2021; H.-L. Wang et al., 2023; Y. Wang et al., 2023). MICP usage has seen an uptake in recent years as a means of soil stabilization. MICP can be achieved through various metabolic pathways such as denitrification and ureolysis (Bhadiyadra et al., 2024; Castanier et al., 1999).

MICP typically involves the introduction of denitrifying or ureolytic bacteria, nutrients, and a source of calcium into the soil, sometimes over several cycles. The distribution of precipitated calcium carbonate is not always uniform due to the inherent spatial variability of soil structures (Lark & Webster, 2006) as well as the change in soil properties caused by the previous cycles (DeJong et al., 2011). For example, the calcium carbonate precipitated during the initial cycles could reduce the hydraulic conductivity of the treated soil which in turn restricts the percolation of nutrients and calcium sources into deeper parts of the soil during the subsequent cycles. This could result in an uneven distribution of precipitated calcium carbonate throughout the treated soil which subsequently affects the behavior of the treated soil under loading. The spatial variability in the precipitated calcium carbonate has been reported in small-scale laboratory soil samples treated with MICP (O'Donnell et al., 2017; Pham et al., 2018). The spatial variability could appear in two general manners. Sometimes, the amount of precipitated calcium carbonate randomly varies throughout the treated samples. In other cases, the amount of precipitated calcium carbonate decreases as the distance from the injection port (where the nutrients and calcium source are injected into the soil) increases until at some distance from the injection port, where no calcium carbonate is precipitated. The latter case is more common. The spatial variability in the precipitated calcium carbonate is expected to be even more pronounced in large-scale field applications (Moug et al., 2022; van Paassen et al., 2010; Zeng et al., 2022).

Even though MICP has been widely studied, very few investigations have been conducted on the effects of spatial variability in the precipitated calcium carbonate on the mechanical behavior of MICP-treated soils. This study aims to analyze the effect of spatial variability on the compressive strength of MICP-treated small-scale samples. To achieve this goal, 3D finite volume analyses were used to simulate the stress-strain behavior of small-scale MICP-treated samples under triaxial compression tests. Experimental data from a series of consolidated drained triaxial compression tests on untreated and MICP-treated samples conducted by (Gao et al., 2022) were used to validate the Finite volume model. The validated model was then used to conduct random finite-volume analyses to investigate the effects of spatial variability on the stress-strain behavior of the MICP-treated samples (Gao et al., 2022).

MATERIALS AND METHODS

Gao et al., (2022) conducted a series of consolidated drained triaxial compression tests on untreated and MICP-treated Ottawa sand. For their MICP treatment experiments, they cultivated denitrifying bacteria from wetted garden soil and used a large-volume circulation technique to stabilize the Ottawa sand through denitrification-MICP. They treated several samples with different treatment cycles. Finally, they conducted consolidated drained triaxial compression tests on treated and untreated samples by monotonically shearing the samples to 25% axial strain at 0.05 mm/min axial strain rate under 50, 100, and 200 kPa effective confining pressures. In this study, a 3D finite volume model (FVM) was developed to numerically simulate the stress-strain behavior of MICP-treated and untreated Ottawa sand under consolidated drained triaxial compression tests. The results of the experiments conducted by Gao et al., (2022) were used to validate the numerical model. The geometry of the 3D model developed in this study is shown in Figure 1. The dimensions were chosen based on the experimental setup, and the soil in the numerical model was divided into 1024 finite volumes.

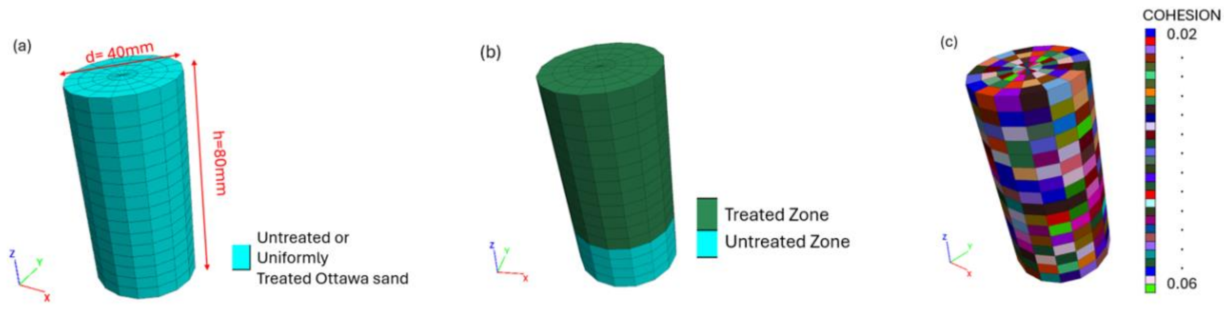

Figure 1. The 3D geometry of the validation finite volume model: a) shows an example of either untreated or uniformly treated Ottawa sand sample b) shows an example of the RFVM model used to investigate the variability in calcium carbonate precipitation (treated zone) due to distance from the injection point (in this example the precipitation only occurred in the top ¾ of the sample volume). c) shows an example of the RFVM model with randomly distributed cohesion in a treated sample.

Three FVM models were developed, each with one of the three initial confining stresses used in the experiments, i.e., 50, 100, and 200 kPa, applied to the surfaces of the sample. A fixed boundary condition was applied at the bottom of the sample, and a constant displacement was applied to the top surface of the sample to simulate the monotonic axial strain used in the experiments. The strain softening/hardening constitutive model was used to simulate the soil behavior. The material properties of the Ottawa sand used in the numerical model before and after yield are summarized in Table 1.

Untreated			Treated		
Plastic strain (%)	Cohesion (kPa)	Friction Angle (degrees)	Plastic strain (%)	Cohesion (kPa)	Friction Angle (degrees)
0	0.05	30	0	0.05	30
0.02	0.05	30	0.02	0.06	33
0.13	0.05	30	0.13	0.07	34
0.3	0.05	30	0.3	0.07	32
0.5	0.05	30	0.5	0.07	30
0.8	0.05	30	0.8	0.07	26
1.3	0.05	30	1.3	0.07	20
2	0.05	30	2	0.07	20

Table 1. Strength properties for both untreated and treated Ottawa sand used for validation finite volume model

The developed deviatoric stress and axial displacement at the top surface of the sample were monitored during the steps of the FVM simulations. The deviatoric stress-axial displacement simulated by the model was compared to the deviatoric stress-axial displacement of the experiments on untreated samples to validate the model. The material properties were then changed to those shown in the right column of Table 1 to simulate the MICP-treated samples (only 10 cycle treatment results were used) assuming that the precipitation was uniform, i.e., no spatial variability. This simplifies the RFVM analyses conducted in the next steps. The deviatoric stress-axial displacement simulated by the model was compared to those of the 10-cycle treated experiments to further confirm that the model can simulate the effects of MICP treatment on the stress-displacement curves.

After validating the ordinary FVM models, the validated model was used to conduct RFVM analyses and investigate the effects of the two types of spatial variabilities on the deviatoric stress-axial displacement behavior of treated soil. To simulate the effects of spatial variability in the amount of precipitated calcite, random values of cohesion (values randomly varied between the cohesion used for untreated and treated soils) were assigned to each of the 1024 finite volumes in the model. An example of such a model is shown in Figure 1c. The model was then executed multiple times (as the cohesions are assigned randomly, they change each time that the model is executed) and the change in the deviatoric stress-axial displacement simulated by the model was monitored.

To simulate the effects of spatial variability in the extent (maximum precipitation distance from the injection port) of precipitated calcite within the soil matrix, the soil was divided into four equal layers along its height (in z-direction). The model was then executed several times, each time 1, 2, or 3 of the layers were considered treated (representing the areas with calcite precipitation) and the remaining layers were considered untreated. Figure 1b, for example, shows a case where the top three layers were considered treated, and the bottom layer was considered untreated (representing a case where precipitated calcium carbonate during the initial cycles of treatment clogged the soil pores and did not allow nutrients to reach to the bottom quarter of the sample and precipitate calcium carbonate). It is worth mentioning that there probably is spatial variability within the treated layers in this case as well. However, to separate the effects of variability in the extent of precipitated calcite and the variability in the amount of precipitation, the treated layers in these models were considered uniform. This will allow us to better understand and compare the importance of each type of variability.

The material properties are shown in the left column of Table 1 (untreated column) were used for untreated layers. The material properties are slightly higher than those shown in the right column of Table 1 (treated column) were used for the treated layers. The higher values were used because, when the calcium carbonate precipitated during the initial cycles of treatment restricts the percolation of nutrients and calcium sources into deeper parts of the soil during the subsequent cycles, more calcite is precipitated closer to the injection port. This amount could be more than the amount that would have been precipitated if calcium carbonate precipitated evenly throughout the sample (which is represented by the cohesion used for uniformly treated soil shown in Table 1).

RESULTS AND DISCUSSION

Figure 2 shows the comparison between the experimental and FVM-simulated deviatoric stress-axial displacement of the untreated soil Samples. The results show that the FVM-simulated stress-displacements are in good agreement with the experimental results. Figure 3 shows the experimental and FVM-simulated (assuming a uniform distribution of precipitated calcite) deviatoric stress-axial displacement of samples treated with 10 cycles of denitrification treatment.

Again, the simulated and experimental data are in good agreement which confirms the validity of the developed model.

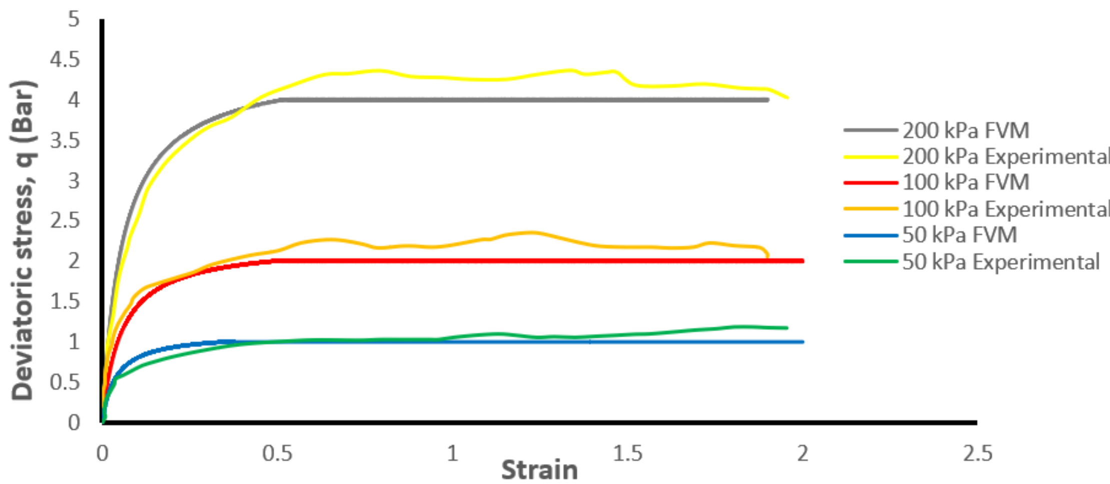

Figure 2. Experimental and FVM simulated deviatoric stress-axial displacement of the untreated soil samples.

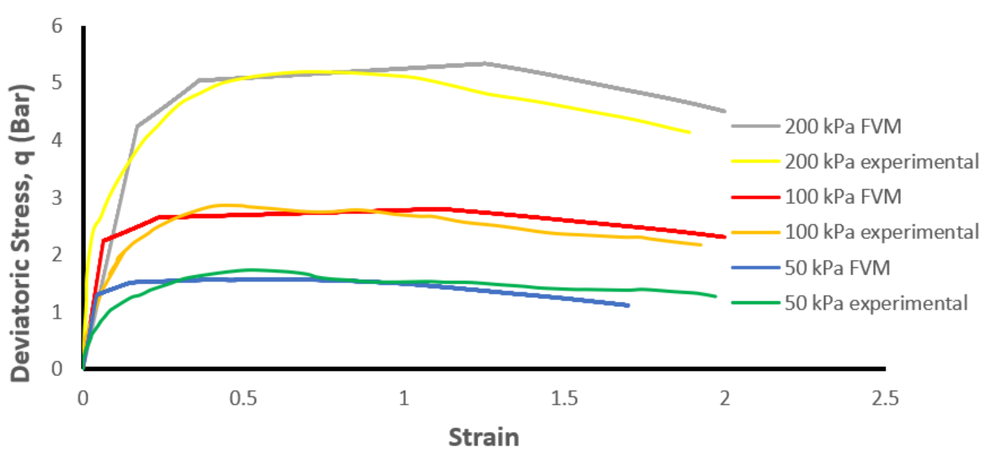

Figure 3. Experimental and FVM simulated deviatoric stress-axial displacement of the soil samples treated with 10 cycles of Denitrification MICP (uniform distribution in the amount of calcium precipitate)

Figure 4 shows a few examples of the FVM-predicted stress-displacement behavior of treated samples with random variability in the amount of calcite precipitate. The experimental results are also shown in this figure for reference. Comparing Figure 3 (where uniform precipitation was assumed) with Figure 4 (where a random distribution of precipitation is considered), shows that the spatial variability in the amount of precipitated calcium carbonate has a small influence on the behavior of treated soil. This type of spatial variability reduces the peak (yield) stress of the treated samples compared to a treated sample with uniformly distributed precipitation, but this reduction is not significant. The influence is more pronounced under lower confining stresses and as the confining stress increases, the influence of the spatial variability in the amount of precipitated calcium carbonate becomes less significant. This is only true if calcite is precipitated everywhere but at different proportions, i.e., there is no large continuous section of the sample without any or with extremely small amounts of precipitated calcite. The cases where calcite was not precipitated (or extremely low amounts were precipitated) within a large continuous section of the sample were not investigated in this study.

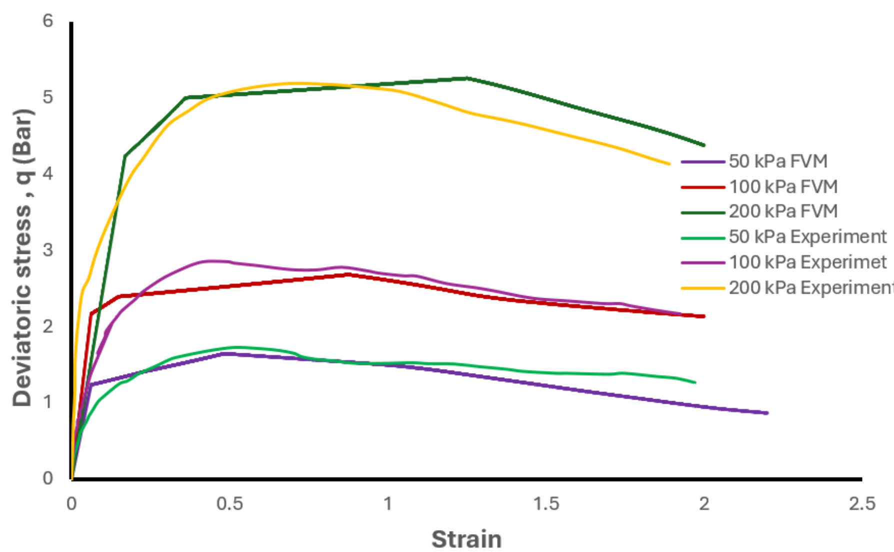

Figure 4. Experimental and FVM simulated deviatoric stress-axial displacement of the soil samples treated with 10 cycles of Denitrification MICP (random variability in the distribution in the amount of calcium precipitate)

Figure 5 shows some examples of the RFVM-predicted stress-displacement behavior of treated samples (10 cycles) with random variability in the extent of calcite precipitate under 50, 100, and 200 kPa confining stresses, respectively. The experimental results are also shown in the figures for reference. As can be seen from these figures, spatial variability in the extent of calcite precipitation has a more pronounced effect on the stress-strain behavior of treated samples compared to the spatial variability in the amount of precipitated calcium carbonate (without a continuous section with no precipitation). This type of spatial variability also reduces the peak (yield) stress of the treated samples compared to a treated sample with uniformly distributed precipitation, but this reduction is more significant (compared to the spatial variability in the amount of precipitation). Similar to the previous case, the effects of spatial variability in the extent of calcite precipitation on stress-strain behavior decrease as the confining stress increases.

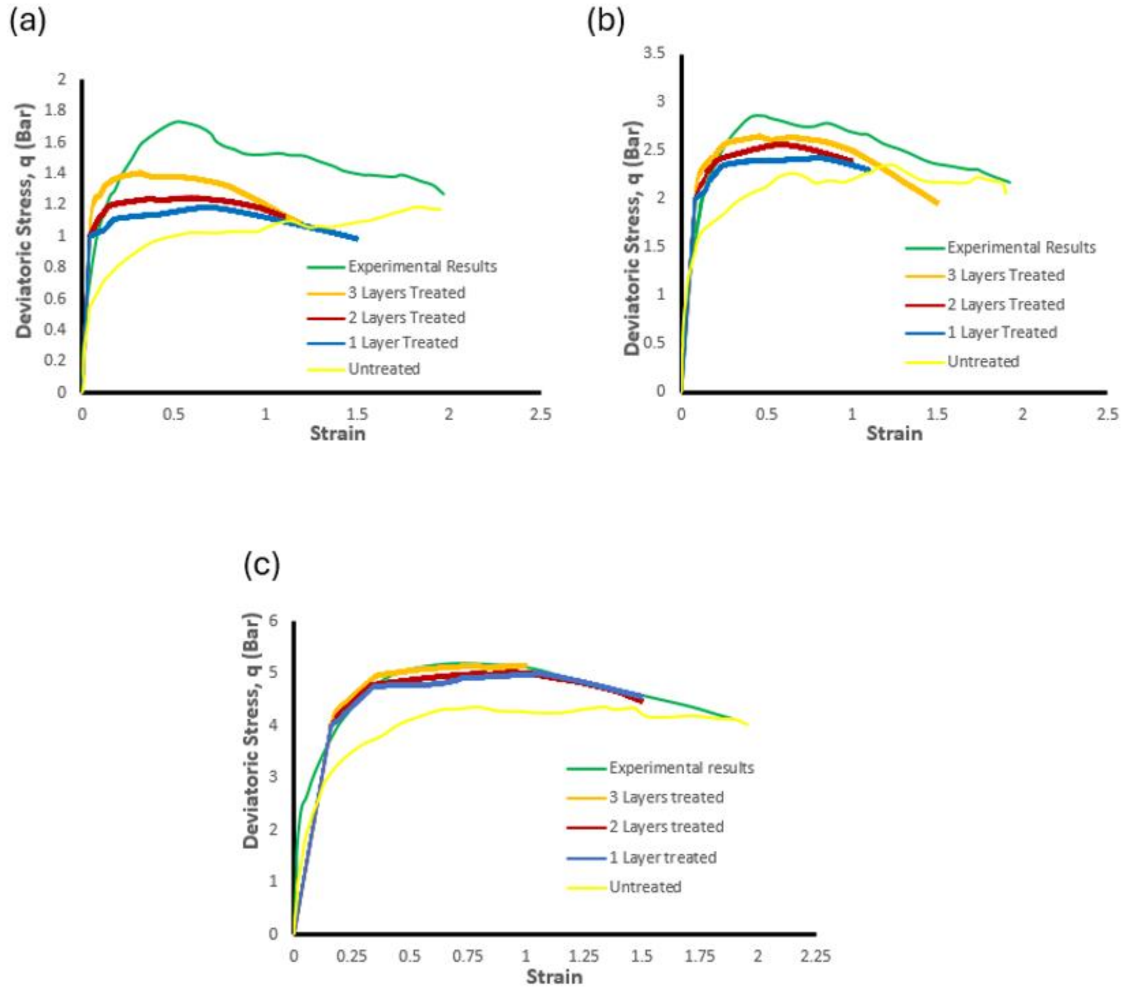

Figure 5. Experimental and RFVM simulated deviatoric stress-axial displacement of the soil samples treated with 10 cycles of Denitrification MICP under a): 50 kPa, b):100 kPa, and c): 200 kPa confining stress (spatial variability in the extent of calcite precipitation).

Figure 6 shows the Mohr-Coulomb failure envelopes of untreated, uniformly treated (experimental data that was assumed uniformly treated), and treated with spatial variability in the extent of precipitation. The results show that as the number of treated layers decreases (representing more precipitation near the injection port and no precipitation away from the injection port), the failure envelope moves farther away from that of the uniformly treated case and closer to the untreated failure envelope. The failure envelopes for the treated samples with the spatial variability in the amount of precipitated calcite were all slightly lower but very close to the uniformly treated sample (not shown in the figure).

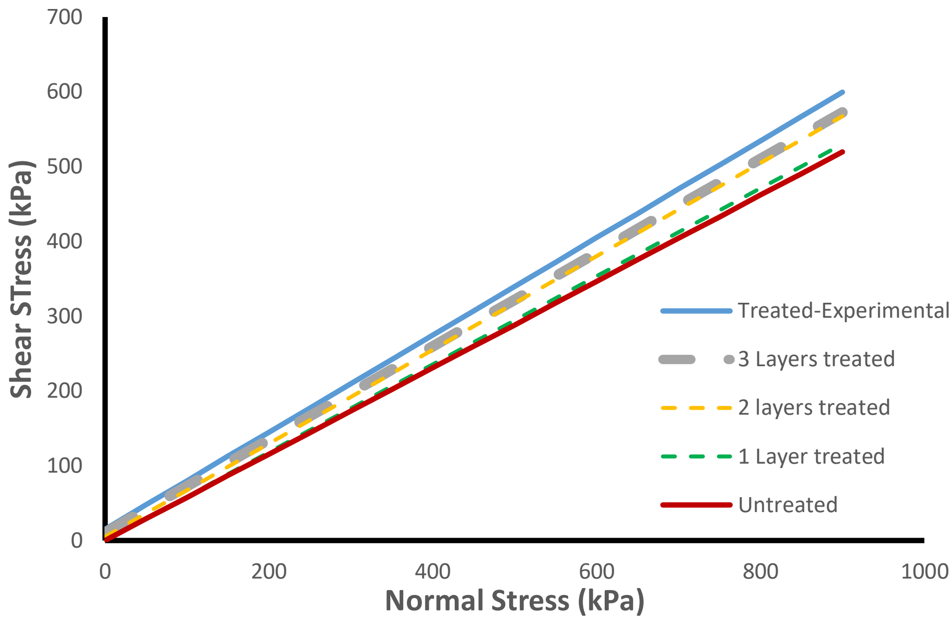

Figure 6. Experimental and RFVM simulated shear stress-normal stress of the soil samples treated with 10 cycles of Denitrification MICP under50,100 & 200 kPa confining stress (spatial variability in the extent of calcite precipitation)

CONCLUSION

The effects of spatial variability in the MICP-induced precipitation of calcium carbonate in soil samples on the mechanical behavior of treated soils were investigated in this study using RFVM. Two types of spatial variability, i.e., spatial variability in the amount (percent by weight) and the extent (maximum precipitation distance from injection port) of precipitated calcite were studied. The results showed that both types of spatial variability affect the stress-strain behavior of the treated soil and reduce the peak (yield) stress of the treated samples compared to a treated sample with uniformly distributed precipitation. The effects of spatial variability in the amount (if there is no continuous section of the sample with no precipitated calcite) are significantly less than the effects of spatial variability in the extent of precipitation. In both cases, however, the effects of spatial variability decreased as the confining stress increased.

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