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Investigation into the short-term behavior of silty sand stabilized with colloidal silica

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Abstract. Injection in soils using traditional materials such as cement grout has its inherent shortcomings and lacks the potential for further development in industrial applications. Accordingly, application of novel materials for injection in soils with considerable fine contents for stabilizing and even making the soils impermeable is suggested. Among different stabilizers that are injectable in soils with fine materials, colloidal silica seems very suitable due to its very low viscosity, nontoxicity in nature, and adjustability of setting time for slow injection in fine soils. In this research study, laboratory tests were performed to examine the effect of colloidal silica on the strength parameters and the short-term behavior of silty sand. For characterizing the soil stabilized by colloidal silica, the silty sand samples with different silt values, in both unstabilized and stabilized conditions, were prepared with different concentrations of the stabilizer. Forty-five uniaxial tests and 75 unconsolidated-undrained compressional triaxial tests were conducted. An increase in the undrained cohesion of all samples was observed. On the other hand, two different trends were observed in the alteration of the undrained internal friction angle of soils with low and high fine contents.

1. Introduction

Stabilization by injection is a technique for filling the pores of soils or cracks and the joints of rocks to improve their permeability and mechanical properties. The three general types of injectable materials are: suspension state grout, emulsion state grout, and soluble state grout. The suspension state grout includes clay, cement, and lime mixed with water, whereas the emulsion state grout includes water and bitumen. The soluble state grout encompasses a wide range of chemicals [1].

Only emulsion and soluble grouts are applicable in fine-grained soils and suspension grouts are usually of no use. The first advantage of chemical grouts lies in their low viscosity and suitable control of setting time. However, their disadvantages are very likely emanation of some types of toxicity in nature and the relative cost of these materials in comparison with other grouts. Some types of chemical grouts include sodium silicate, lignosulfite, acrylamide, calcium acrylate, and resins such as resin epoxy and resorcinol formaldehyde [2].

Considering the efficiency of silicates in soil stabilization and their chemical and biological neutrality, there is a great tendency towards these materials. Recently, application of nanotechnology in silicate based chemical grouts has resulted in fabrication of colloidal silica, which has remarkable properties in terms of chemical injection. According to Towhata (2008), colloidal silica due to no deterioration in mechanical strength (no weathering), uniform seeping of liquid,

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and not being harmful to human health [3] is a suitable stabilizer for use in soil medium.

As seen earlier in published researches, stabilization of soil by colloidal silica can improve soils by increasing cyclic and post-cyclic strengths, increasing uniaxial strength, decreasing soil settlement and cyclic deformation, and making the stabilized soil impermeable. Thus, stabilizing the soils by injecting colloidal silica can be applied in practice in order to trigger liquefaction, increase bearing capacity, stabilize slopes, and form subsurface barrier.

So far, the effects of stabilizing the soil by colloidal silica on its mechanical properties have not been investigated comprehensively; therefore, in this research, the effects of colloidal silica on the mechanical parameters of silty sand with different amounts of silt have been investigated.

1.1. Background

Persoff et al. (1999) performed permeability and uniaxial tests on sandy soil samples stabilized by colloidal silica. After one month, three months, and one year, they found that the uniaxial strength of the sandy soil stabilized by colloidal silica was dependent on the concentration of silica particles in the solution. According to their tests, the uniaxial strength reached over 400 kPa in some samples. Furthermore, the hydraulic permeability of the sand stabilized by colloidal silica grout decreased to less than 10^{-7} cm/s with increase in concentration [4].

Gallagher and Mitchell (2002), in a study to stabilize liquefiable sands, indicated that use of colloidal silica 5% would result in a proper strength against cyclic deformation [5].

Diaz Rodriguez et al. (2008) in a study of natural liquefiable sand stabilized with colloidal silica grout found that its cyclic resistance was influenced by the initial relative density of the sand, the initial effective vertical stress, and the colloidal silica concentration. As the amount of initial effective vertical stress on stabilized sample increased, dilation progressively contributed more than cementation to the cyclic resistance of treated sands; consequently, dense sands (which dilated more than loose sands) exhibited greater liquefaction resistance at higher initial effective vertical stress [6].

Gallagher and Lin (2009) stabilized the sand samples in several cross sections in their constructed injection columns and conducted uniaxial test. Their study illustrated the usefulness of uniaxial tests in indicating the degree of stabilization of the samples. Based on their tests, the average uniaxial strength for the sand stabilized by colloidal silica 5% was between 40 and 60 kPa [7].

Gallagher et al. (2007) conducted physical modelling of Nevada 120 loose sand soil stabilized by colloidal silica 6%. The relative density of the soil, prepared by dry pluviation, in centrifuge tests was 40%. To ensure that soil pores were totally filled by the stabilizer, the injected grout volume was 1.5 times bigger than the volume of the pores. Based on the performed measurements, the tested grout was changed into shaking solid gel after 56 hours. Then, after 240 hours of treatment (four times longer than the gelation time), the model underwent the tests. After injection and treatment of the soil, 21 samples were extracted from the centrifuge tests container (by trimming method) and uniaxial tests were performed. Test results revealed that the uniaxial strength of the treated soil varied between 16 kPa and 61 kPa [8].

Conlee et al. (2012) performed centrifuge model tests on sand slopes stabilized by colloidal silica. They compared the liquefaction and deformation responses of the unstabilized loose sand slope with those stabilized by colloidal silica with 4, 5, and 9 weight percent. The following results were obtained from their study [9]:

- With increase in the concentration of colloidal silica, the soil settlement gradually diminished;
- Stabilization by colloidal silica in soil slopes located on liquefiable soil layers significantly prevented lateral spreading of the slope;
- The sand stabilized by colloidal silica caused a higher tip resistance in the cone penetration test. Furthermore, the shear wave velocity increased in the stabilized soils. Because the gelled sand matrix provided significant shear resistance, which also caused the expanded dilation region for colloidal silica stabilized sand during phase transformation under monotonic loading.

2. Materials and methods

To fabricate the silty sand samples, Babolsar sand and Babol silt with different mixing percentages were used. The physical specifications of these materials are provided in Table 1.

Table 1. Physical specifications of materials.

Soil type	Babolsar sand	Babol silt
Classification (unified method)	SP	ML
Fine content	0.3%	87.7%
G_s	2.74	2.55
D_{10} (mm)	0.10	—
D_{50} (mm)	0.18	—
LL	—	37
PI	—	11

Figure 1. Dr. Khan Industrial Consultants' CS30 colloidal silica.

CS30 colloidal silica of Dr. Khan Industrial Consultants was used in this testing program. According to Dr. Khan Industrial Consultants' product information, CS30 has 30 wt% silica, a specific gravity of 1.210, and a specific surface area of 210 m^2/g with milky white color (Figure 1). Before dilution, the pH of the solution was 10.0 and the viscosity was 5 cP.

2.1. Sample preparation

According to Persoff et al. (1999), to prepare samples most accurately representing field conditions, one can inject the grout into the ground, forming a bulb, excavate the bulb, and core or carve out a cylindrical sample for testing. Such a sample is subject to many variables that are difficult to control, including the techniques of injection and sample recovery, the permeability and heterogeneity of the soil, and how completely the grout fills the pore space. Injecting grout into laboratory sand packs eliminates soil heterogeneity and encourages uniform penetration of grout by confining its flow to one direction, but does not guarantee that the filling of pore space by the grout will be the same in all samples. This second method sacrifices representation of field conditions without maximizing sample reproducibility. Systematic determination of the effects of controlled variables on properties of the grouted samples requires that samples be prepared as reproducibly as possible [4]. Therefore, the method of sample preparation is chosen to maximize reproducibility.

Different samples containing clean sand and silty sand with different fine contents (silt percentages of 0, 10, 20, 30, and 40% of the sample weight) are used in this study. According to ASTM, to control the density of soil samples with fine contents (particles finer than 0.074 mm or passing sieve # 200) lower than 15%, a variety of laboratory tests can be used, including relative density (Dr) definition, minimum void ratio, and maximum void ratio [10,11] determination tests or compaction percentage (Rc) definition and Proctor test [12]. However, it is not possible to perform the minimum and maximum void ratio tests on soil samples with fine content percentages of over 15% [10,11]. Accordingly, in this research, in order to have consistent control over the density of the samples, compaction percentage (Rc) parameter and standard compaction test are employed. The compaction percentage of the samples is chosen to be 93% in all tests. This compaction percentage is expected to be equivalent to a relative density lower than 65% (i.e., the sample is in medium-compact conditions).

To begin the fabrication of the samples, the weight of each constituent is determined. For this purpose, considering the compaction percentage of the samples (medium dense samples with compaction percentages of 93% of the standard compaction), the specific dry weight of the sample is determined. Thereafter, having the volume of the mould, the dry weight of the soil is calculated. Next, based on the relative density of each soil sample, the volume of the voids is specified using weight and volume relations. The volume of the stabilizer is then calculated in a way that it fills all void spaces of the soil. Finally, the materials of interest are mixed with each other and the samples are fabricated by wet soil tamping method.

2.2. Age of the samples in the experiments

Colloidal silica-stabilized samples with different ages have been used in laboratory tests performed by different researchers. For example, Persoff et al. (1999) [4] and Diaz Rodriguez et al. (2008) [6] used samples with an age of 7 days for the tests. Gallagher et al. (2007) conducted tests on samples with an age 4 times, i.e., as long as the gelation time [8]. Gallagher and Mitchell (2002) proposed that the suitable time for the tests was at least 10 times longer than the gelation time [5]. Liao et al. (2003) carried out their tests 7, 14, and 28 days after the fabrication of samples [13].

To determine the suitable age for performing the experiment, uniaxial tests are used. Uniaxial tests are done by ELE apparatus according to ASTM D-2166 standard [14] using axial strain rate of 1.2 percent per minute. These tests are carried out on the stabilized soil samples with different ages. Uniaxial tests are done on clean sand soil samples stabilized by colloidal silica 5% (the most diluted state in this research). In ages of 1-21 days off the fabrication time, two to three samples are tested. Based on the 45 uniaxial tests performed in this section, the average uniaxial strength versus sample age relationship is obtained and presented in Figure 2.

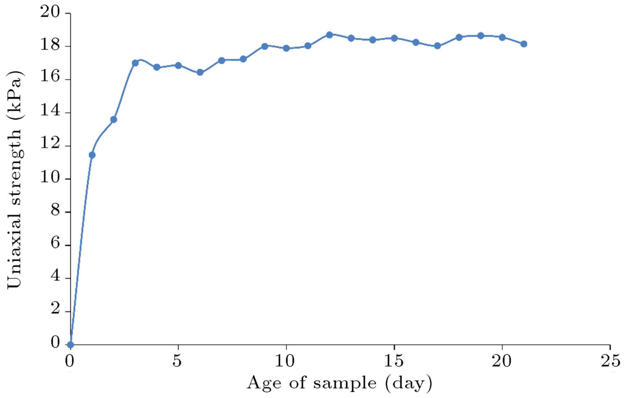

Figure 2. Variation of uniaxial strength of clean sand stabilized by 5% colloidal silica versus age of samples.

According the results of uniaxial tests shown in Figure 2, the average strength of clean sand stabilized by colloidal silica 5% in this study is approximately 18 kPa. Considering the fact that uniaxial strength of stabilized sample is affected by sample relative density and colloidal silica concentration, the results of this study are comparable to the results of other published researches, e.g., the study done by Gallagher and Mitchell (2002) [5] with about 32 kPa and Gallagher et al (2007) [8] with more than 16 kPa.

As can be seen in Figure 2, up to three days, the uniaxial strength of the sample has a sharp ascending trend. After three days, the rate of growth of uniaxial strength diminishes significantly. Therefore, the age of performing tests in this research is chosen to be three days.

2.3. Unconsolidated-undrained triaxial tests

In order to evaluate the undrained behavior of clean and silty sand soils stabilized by colloidal silica, 75 unconsolidated-undrained triaxial tests were conducted by ELE triaxial device according to ASTM D-2850 standard [15]. The triaxial device was a manual one and the strain, force, and pressure were read by operator. The tests were carried out by the strain controlled method with axial strain rate of 1% per minute for the samples with the diameter of 52 mm and height of 104 mm, and compaction percentage of 93%. The tests were performed on clean and silty sands (10, 20, 30, and 40% silt) under stabilized and unstabilized conditions (with colloidal silica 5, 10, 20, and 30%). Based on the results obtained from the uniaxial tests, all of the stabilized samples were tested at the age of 3 days off the fabrication time and under the confining pressures of 400, 600, and 800 kPa.

3. Results

After conducting the unconsolidated-undrained triaxial tests on the samples, different corrections to sample area and membrane force effect were performed according to the standard. Consequently, the diagram of stress-strain changes and Mohr circles of the soil samples were plotted under undrained loading conditions in order to determine internal friction angle and soil cohesion. Some stress-strain curves obtained from the tests are presented in Figure 3.

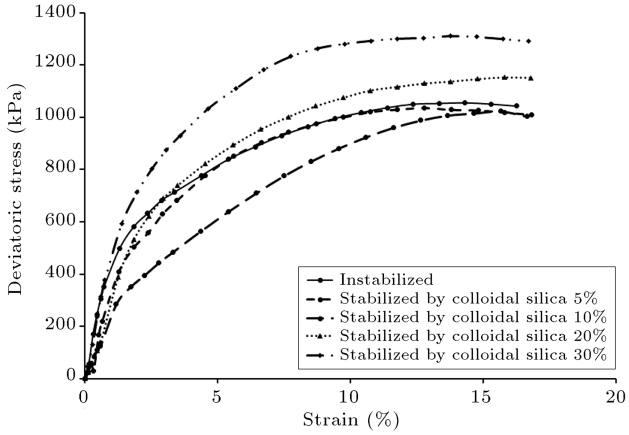

Figure 3. Stress-strain curves for clean sand stabilized by different colloidal silica concentrations under confining pressure of 400 kPa.

Note that in the course of the majority of the tests, the soil samples were changed into barrelling form under loading and no shearing surface was observed in the samples. According to the standard, the maximum axial stress was equal to the stress in 15% axial strain.

The results of unconsolidated-undrained triaxial tests performed at this step of the experiments are presented in Table 2.

4. Discussion

The deviator stress versus stabilizer concentration obtained through unconsolidated-undrained triaxial tests is presented in Figure 4. As can be seen by the curves in Figure 4, the trend of changes in the undrained resistance of soil in the unconsolidated-undrained tests with different confined pressures follows two different patterns. The first pattern is related to the samples with fine contents lower than or equal to 20%, in which with increase in the concentration of the colloidal silica, the undrained resistance of soil is first descending and then ascending. The second pattern is associated with the samples with fine contents of over 20%, in which with increase in the concentration of the colloidal silica, the undrained strength of the soil has an ascending trend.

In order to investigate the reason for the above observations, taking the parameters affecting the undrained shear strength of the soil under closer scrutiny reveals that, as shown in Table 2 and Figure 5, with all of the different percentages of fine content, the increase in the concentration of the colloidal silica stabilizer results in elevated value of soil cohesion in

Table 2. Unconfined-undrained triaxial test results for various samples.

Silt content (%)	Colloidal silica dilution (%)	Deviatoric stress at confining pressure			c (kPa)	Φ (degree)
		400 kPa	600 kPa	800 kPa		
0	0	1055.6	1551.2	2082.1	5	34
	5	1035.8	1488.8	2017.6	8	33
	10	1018.3	1457.4	1967.7	13	33
	20	1148.2	1594.1	2061.8	63	32
	30	1311.0	1702.4	2098.9	151	30
10	0	1146.9	1585.2	2232.4	2	35
	5	984.5	1384.7	1899.9	10	32
	10	775.1	1111.2	1479.0	18	28
	20	921.8	1233.9	1606.3	67	27
	30	1321.8	1670.6	2062.8	168	29
20	0	930.7	1312.6	1816.0	3	32
	5	765.7	1100.7	1476.5	13	28
	10	607.6	904.8	1168.1	19	24
	20	826.7	1022.9	1402.8	67	25
	30	1181.6	1511.4	1830.3	166	27
30	0	122.1	173.9	222.8	10	6
	5	222.3	305.8	409.3	12	11
	10	272.2	376.3	486.6	22	12
	20	582.8	798.6	986.8	67	20
	30	984.2	1206.4	1457.0	170	22
40	0	62.5	80.2	91.0	18	2
	5	120.5	155.7	191.8	23	5
	10	217.9	292.9	380.9	21	10
	20	447.3	590.2	719.5	69	15
	30	922.9	1134.4	1353.4	170	20

undrained conditions. This phenomenon is due to the gelation property of colloidal silica and attachment of soil particles to each other, which is observed in all soil samples. The cohesion of the samples with different fine contents begins with natural cohesion of the soil and increases up to an almost constant value, which is equivalent to the cohesion of colloidal silica at a certain concentration.

The effect of stabilization on the internal fraction angle of the soil, as can be seen in Table 2 and Figure 6, has two different trends for various samples. The first trend for the alteration of internal friction angle is observed in clean and silty sand with 10 and 20% silt. In these soils, considering the fact that the behavior of soil under shear is frictional, adding colloidal silica results in filling the roughness across the surface of the soil particles, which results in a reduction in the internal friction angle of the soil. In other words, because colloidal silica is a smooth gel that encases the soil grains, in case of frictional soil, adding colloidal silica results in reduction in the frictional properties of soil. This phenomenon is more dominant if the colloidal silica around the grains becomes thicker, so that by increasing the concentration of colloidal silica on stabilized frictional soils, the undrained friction angle is reduced.

The second trend of altered internal friction angle is seen in sands with silt percentages of over 20%. In these soils, the fine part fills the inter-particle space of coarse particles and results in separation of coarse

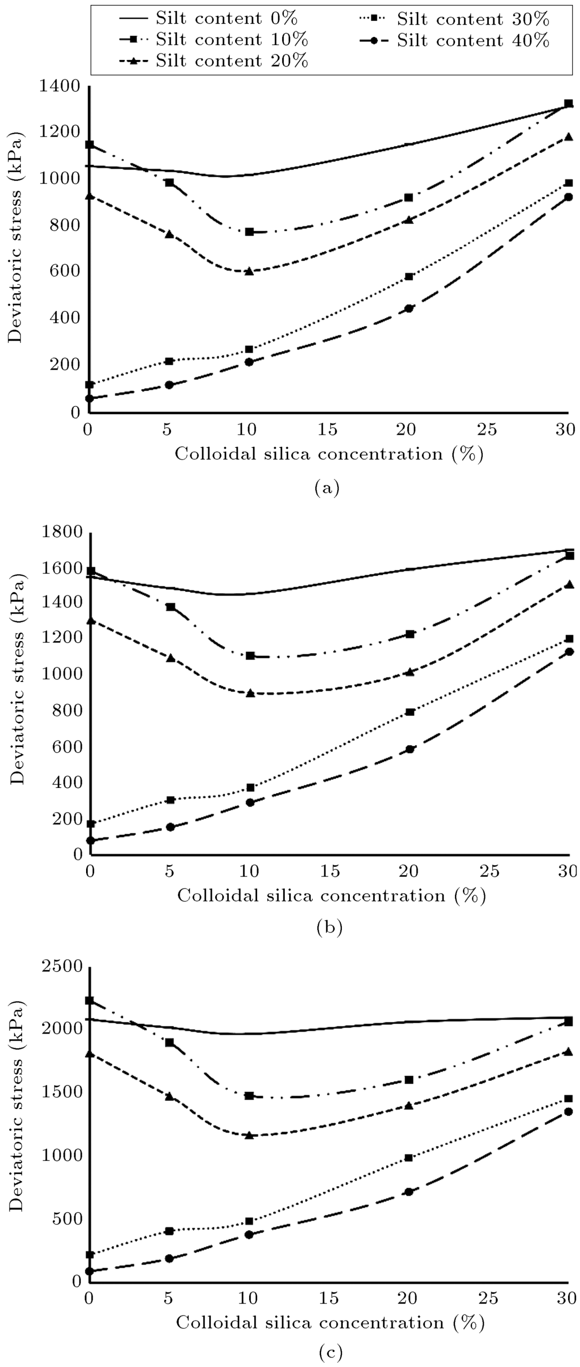

Figure 4. Variation of deviatoric stress with increase in colloidal silica concentration with confining pressures of (a) 400 kPa, (b) 600 kPa, and (c) 800 kPa.

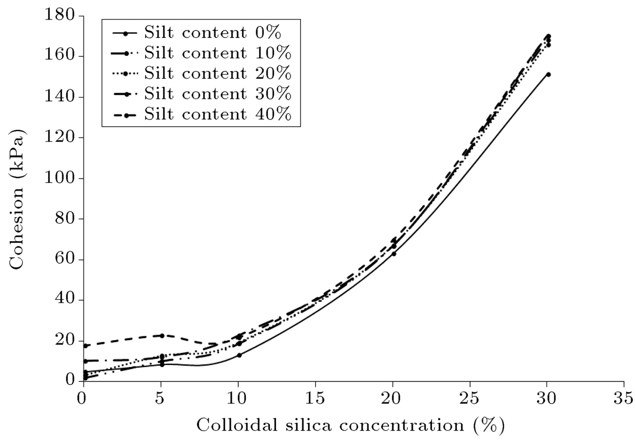

Figure 5. Variation of stabilized sample cohesion by increasing colloidal silica concentration.

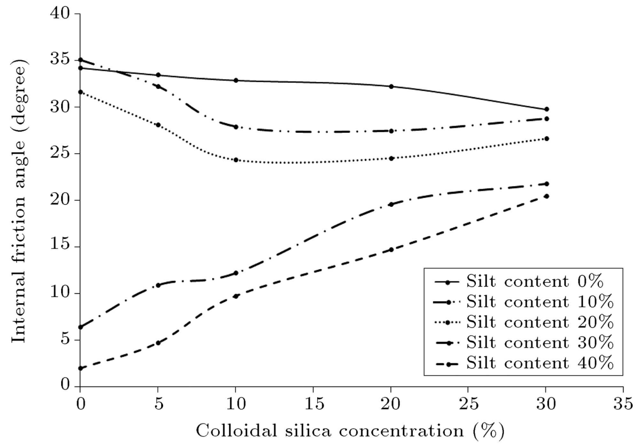

Figure 6. Variation of internal friction angle for stabilized sample by increasing colloidal silica concentration.

grains from each other [16]. Accordingly, rather than the friction of coarse-grained particles, the mechanism of soil shear loading is determined based on cohesion of fine-grained particles. For this reason, it is observed that the initial internal friction angle of these soils is low, but with increase in the concentration of the stabilizer, the silt fine-grained particles are attached to each other with a stronger bond and form a soil similar to a coarse-grained soil. Therefore, with increase in the concentration of the stabilizer in the fine-grained soils, the internal friction angle grows. This phenomenon is similar to the observations of Lade and Overton (1989) for soils stabilized by cement [17].

With a more careful look at Figure 6, it is observed that in the sand with 10 and 20% silt, with increase in the concentration of colloidal silica, the trend of changes in the internal friction angle is first descending and then ascending. The reason for this phenomenon is the twofold mechanism of silty sand under shear, which is controlled by both particle friction and cohesion of fine-grained soil. At low concentrations of the stabilizer, the first trend mentioned above leads to diminished friction angle and with increase in the concentration of the stabilizer, the second trend mentioned above results in increase in the internal friction angle of the soil.

5. Conclusions

Based on uniaxial tests performed on samples stabilized by colloidal silica, considering the setting time of the stabilizer, which was 2 hours, with increase in the sample age up to three days, the uniaxial strength of the sample had an ascending trend. After three days, the rate of the growth of uniaxial strength diminished significantly. Therefore, 3-day samples were found suitable for performing the tests.

For all the different percentages of fine content, increasing the concentration of the colloidal silica stabilizer resulted in increased soil cohesion in undrained conditions. This was due to the gelation property of colloidal silica and attachment of soil particles to each other, which was seen in all soil samples. The cohesion of samples with different fine contents started from initial cohesion of soil and increased up to a constant value, which was the cohesion of colloidal silica at a certain concentration.

In the clean sand and the sand with 10 and 20% fine contents, it was observed that the addition of colloidal silica resulted in smoothing of the rough surfaces of the sand particles, causing a reduction in the internal friction angle of the sand.

In sands with silt percentages of over 20%, it was seen that the initial internal friction angle of these soils was low. However, with increase in the concentration of the stabilizer, the silt fine-grained particles were attached to each other with a stronger bond and formed a soil similar to coarse-grained soil. That is, with increase in the concentration of the stabilizer in fine-grained soils, the internal friction angle increased.

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Conflict of interest

The authors confirm that there are no known conflicts of interest associated with this publication.

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