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AN EXPERIMENTAL STUDY ON STRESS RELAXATION BEHAVIOUR OF CEMENT STABILIZED SANDS

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ABSTRACT

In this study, stress relaxation tests were carried out by keeping cement stabilized sand (CSS) specimens with different particle size distributions and cement contents under various strain levels. Time-dependent decreases in the stress values were collected to better understand the effect of the strain level on the relaxation properties of the cement stabilized sand specimens. In addition, the stress relaxation effect on the uniaxial compressive strength (UCS) values of the CSS specimens was investigated with a series of tests. According to the results obtained from this study, UCS values of the CSS specimens vary depending on the strain level during the stress relaxation. The UCS values were determined to significantly decrease in case of high-stress levels at the initiation of the relaxation, which are close to the peak value. The stress relaxation rate was measured to be rapid in the first minutes and remarkably decrease with an increase in the duration of the relaxation. Cement content was found beneficial to improve the relaxation resistivity of the CSS samples. As another outcome of this study, the fines particle content was determined to cause decreases in the strength values after the stress relaxation effect.

Key words: Cement stabilized sand, stress relaxation, strength loss, time effect in soil mechanics.

1. INTRODUCTION

Stress relaxation and creep are two different phenomena that cause time-dependent changes in strength values of soils and are sometimes confused with each other. The stress relaxation is defined as the time-dependent reduction in stress values in materials under a constant strain. On the other hand, creep means a time-dependent deformation under a constant external stress. Compared to the stress relaxation, it is possible to find more studies on the creep effect in the geotechnical engineering literature. Within previous researches, various parameters like grain size, grain shape, water content, external stress level, loading time, confinement pressure from the second, third axes, *etc.,* have been studied to determine their effect on creep behaviors of soils (Sanchez-Giron *et al.* 2001; Hsieh and Tseng 2008; Kutergin *et al.* 2013; Lade and Karimpour 2015; Levin *et al.* 2019; Zhu *et al.* 2022).

The stress relaxation occurs as a result of the initiation of time-dependent plastic deformation. Even at a stress level where the elastic deformation is induced in a short-term loading, plastic deformations can be observed under the condition of a constant strain level, depending on the time factor. Because of the plasticization, the ability to return to the previous size is relatively or totally lost depending on the duration of the stress relaxation. During the relaxation, the rate of decrease in stress values acting from outside is relatively high at early times and it decreases in later stages. As the stress relaxation is completed and the stress level decreases to zero, the tendency to return to the initial length is completely lost. In other words, a soil sample has no reversal strain change and maintains its length after the completion of its relaxation (Liingaard *et al.* 2004; Kamao 2016; Komurlu 2021). This study is aimed to be beneficial for a better understanding of the stress relaxation effect which is usually neglected in geotechnical engineering designs and analyses.

Creep deformations can occur as a result of long-term exposure to an external stress level. The rate of creep deformation depends on various parameters such as the material's properties, stress level, time, temperature, *etc*. In addition to creep deformations, soil specimens can have time-dependent failure under a high and constant stress level that is close to the strength value. The time-dependent failure situation of samples that have been loaded for a long enough period is referred as the creep failure. Creep is an important time-dependent event for soils under a constant stress such as those resulting from dead loads of buildings (Kwok and Bolton 2013; Xu *et al.* 2018; Chegenizadeh 2020; Liu *et al.* 2022).

If the mechanical parameters of a soil are not sufficient for an engineering work to be carried out, soil improvement applications can be performed. Stabilization by using cement is one of the popular soil rehabilitation methods (Eldessouki *et al.* 2017; Chai *et al.* 2021; Consoli *et al.* 2021; Hartono *et al.* 2021). A cement stabilized soil (CSS) is an engineering mix of soil, water and generally a few amount of cement. With less cement usage, CSS materials have semi-bound particles with engineering properties similar to those of granular materials. Nevertheless, cement content makes an increase in shear, compressive and tensile strength values of CSS materials which can be mixed-in-place using on-site soils or mixed in a central plant using selected soils. In this study, CSS samples were prepared in the laboratory by mixing different sand type soils and the cement binder with different amounts. The main motivation for carrying out this study is to assess whether the stress relaxation event which is generally neglected in geotechnical engineering works has a notable effect on the time-dependent mechanical properties of the CSS type materials. In this study,

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decreases in the stress values owing to the relaxation effect and changes in the time-dependent strength values of CSS samples due to the relaxation were investigated with a series of tests. Details of this experimental study are given in the following section.

2. MATERIALS AND METHODOLOGY

Soil specimens of this study were taken from Giresun city of the Black Sea Region of Turkey. To classify the soil specimens, particle size distribution analyses were carried out using No. 4 (4.76 mm), No. 10 (2.00 mm), No. 20 (0.85 mm), No. 40 (0.425 mm), No. 100 (0.149 mm) and No. 200 (0.074 mm) sieves. Soil specimens with two different particle size distributions were coded as F (with fines particle content) and N (without fines content). It should be noted herein that the difference between the soil samples is using fines particles (< 0.074 mm) in the F coded soil and removing the particles which are finer than 0.074 mm from the N coded soil. The reason for using different soil samples with various particle size distributions is to investigate the fines particle content effect on the relaxation properties of soils. The particle size distributions of soil specimens are given in Fig. 1. Both N and F coded soil specimens have well-graded particle size distributions because they have coefficient of uniformity (C_u) values higher than 6 and coefficient of curvature (C_c) values between 1 and 3 (ASTM D2487-17).

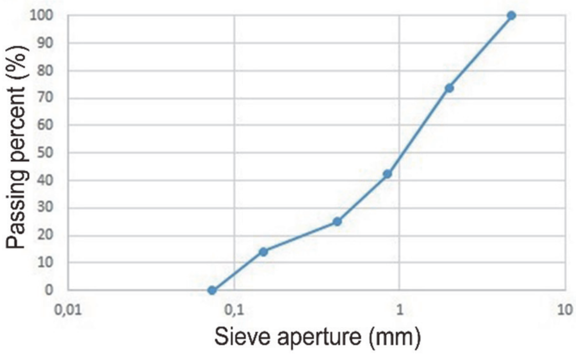
Soil specimens were sieved before tests to prepare them for passing the No. 4 (4.76 mm) sieve to use in the experimental study. To classify F coded soil with 8% content of particles passing the No. 200 sieve, liquid and plastic limits (Atterberg limits) were determined. The famous Casagrande test was carried out for determination of the liquid limit value. The methodology stated in the ASTM D4318-10 coded standard was followed in the Casagrande test. Soil and water mixtures were put in the Casagrande test cup and cut into two parts with the standard groove. The cup of the Casagrande test equipment was then dropped repeatedly by the motor until the groove is closed due to the flow of the soil and water mixture. The liquid limit was determined as the water content for closing the groove due to the impact of 25 blows. In case of a contact length of 13 mm, the test was stopped and the groove was considered to be closed (ASTM International 2010). Liquid and plastic limits of the soil were determined as 41% and 28%, respectively. According to the unified soil classification system (USCS), N and F type soils can be respectively classified as SW (well-graded sand) and SW-SM (well-graded sand with silt).

The water content was calculated as the ratio of mass of water to mass of dry soil. To make dry soil, specimens were heated in the 105°C stove for a day. The plastic limit test is performed by rolling soil rods on the standard glass plate. As stated in the ASTM D4318-10 coded test standard, the plastic limit was determined as the water content of soil rods which just crumbles when it is carefully rolled to a diameter of 3 mm.

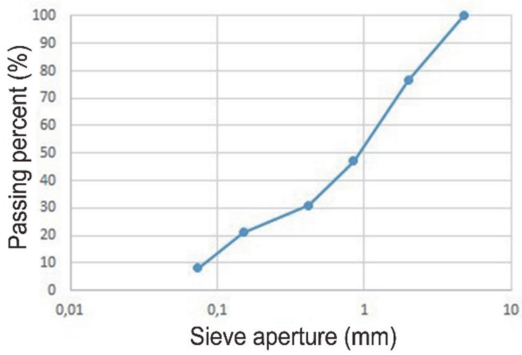
Soil, cement and water were mixed in a plastic basin and homogenized by hand. Cemented soil specimens were filled in cylindrical molds with an inner diameter of 46 mm. The specimens were filled into the molds in three steps and 25 mallet drops were applied to make compaction after each filling step. In the mixes, cement and water ratio is 1/1 by weight. A CEM 1 type ordinary Portland cement was used in the specimens. To investigate the cement content effect, specimens were prepared with two different cement amounts in mixes. The cement amount is respectively 8% and 14% of the total mix (cement + water + soil) by mass in specimens with low (*L*) and high cement contents (*H*). Lengths of the samples were measured precisely and the density values were determined by weighing with 0.001 g sensitive electronic scales after the soil specimens were removed from the cylindrical molds.

The uniaxial compressive strength (unconfined compressive strength) test specimens with the ratio of height to diameter of 2 were kept at the room temperature for a day and removed from the molds later on. The roughness of the up-side end surfaces of the CSS specimens was gently removed by using a snap blade knife to make a smooth contact with the loading platens. Also, it should be noted that the up-side surfaces were flattened by using a mallet when the specimens are newly filled in the molds. The molding and removing from the mold procedures were the same for all specimens. As plastic molds with one slit cut along their lengths were used, specimens were easily removed from their molds by opening the slit. A total of 36 sepcimens were used for testing (Fig. 2).

Some of the specimens were used in the uniaxial compressive strength (UCS) test without having a stress relaxation, and the other ones were kept under various strain levels to investigate time-dependent variations in stress values due to the relaxation. To initiate the stress relaxation effect loading platen movement was stopped at different strain levels under the UCS test press. Then, decreases in the stress values were recorded for different periods. The relaxation tests were initiated after 28 days of curing. UCS tests of the specimens with and without the stress relaxation were performed in the same day after a curing time of 49 days. By this



(a)



(b)

Fig. 1 Particle size distribution graphs of soil specimens: (a) N type sands; (b) F type sands

Fig. 2 Specimens used in this study

way, UCS values of specimens with and without the stress relaxation could be examined comparatively. The loading rate was chosen to be 0.5 mm/min in the UCS test. A sensitive electric motor press with the loading capacity of 50 kN was used to measure the load values during the uniaxial compressive strength test and the stress relaxation process (Fig. 3).

3. RESULTS

Within the stress relaxation tests, the data of stress variations with the change of time was measured as given in Fig. 4. According to the results, the stress relaxation rate was found to decrease with an increase in time. Especially, the change in the stress levels was quite slow towards the end of the tests. Therefore, relaxation tests were finalized after 24 hours, as more than an 80% decrease in the stress level is achieved for the specimens. According to the results, the percentage of change in stress values was found to decrease with increasing cement content. The cement content was found to be an important parameter to influence the relaxation time. Stress relaxation rate was determined to decrease with an increase in the cement content. In comparison to those of the specimens with low cement content, the high cement content caused longer relaxation times. As another outcome, the fines particle content was determined to increase the relaxation rate.

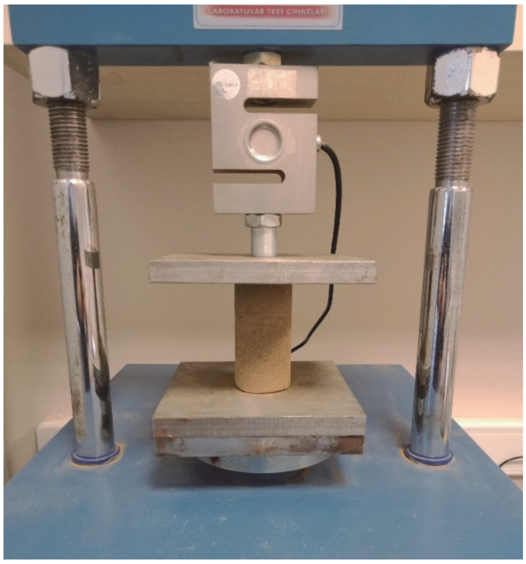


Fig. 3 Uniaxial compressive strength test

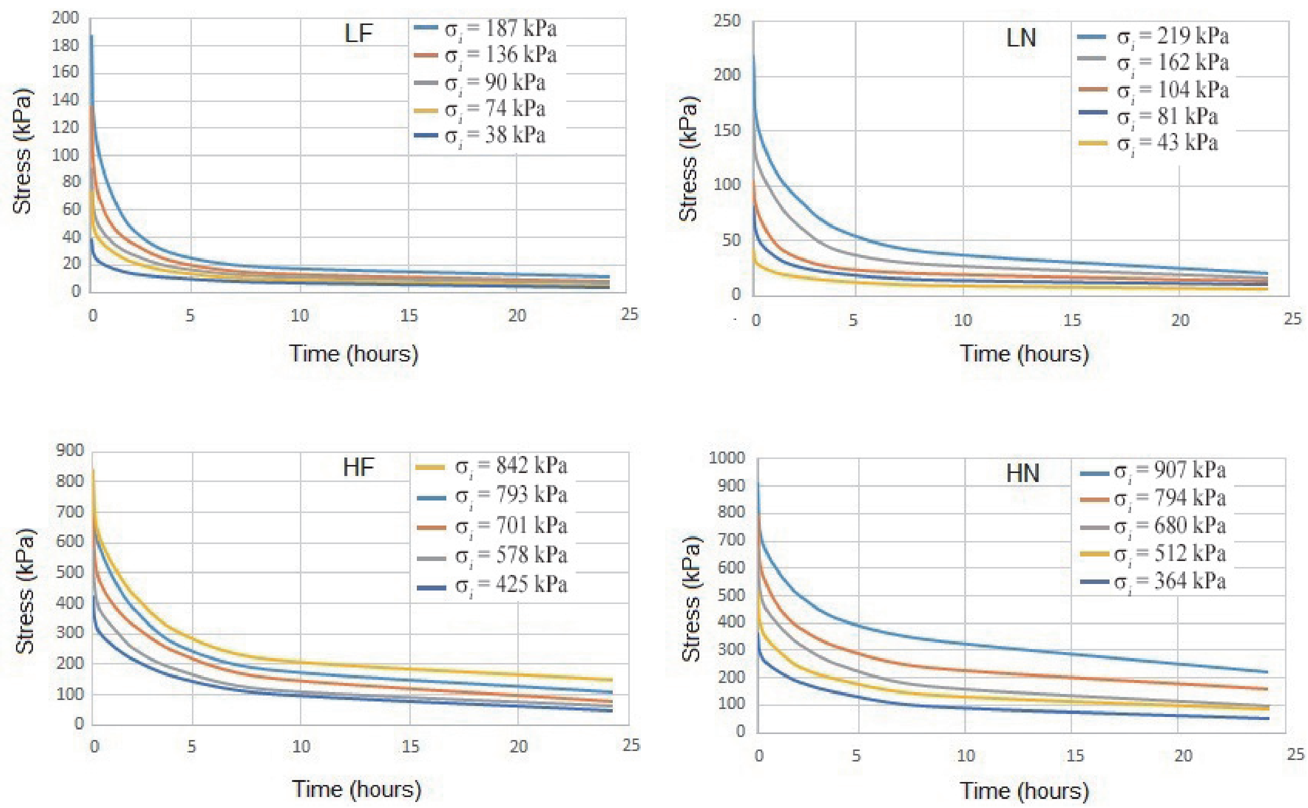


Fig. 4 Stress variations during the relaxation

The stress relaxation was found to have a negative effect on UCS values in case of having higher initial stress values (σ_i) than a threshold level (Fig. 5). According to the results obtained from the UCS test, the stress relaxation was assessed to have a non-ignorable effect for the case of high σ_i values which are close to the strength level. The threshold σ_i value was found to increase with increasing cement content. It can be stated that the resistivity against the strength loss due to the relaxation is improved with an increase in the cement content. UCS values of samples with the low cement content (L) after relaxation were found possible to be lower than the stress level at the initiation of the relaxation (σ_i) when the σ_i value is close to the UCS value of the no-relaxation case. The fines particle content was found to decrease UCS values of the cement stabilized sand specimens as seen in Tables 1 and 2.

Table 1 Uniaxial compressive strength (UCS) values of specimens under no relaxation ($\sigma_i = 0$)

Specimen type	UCS (kPa)	SN	SD (kPa)
LF	204	4	9
LN	251	4	13
HF	937	4	26
HN	1083	4	24

Note: L: specimens with low cement content, H: specimens with high cement content, F: specimens with fines content, N: specimens with no fines content, SN: specimen number, SD: standard deviation

Table 2 Uniaxial compressive strength test results of specimens after stress relaxation

Specimen type	σ_i (kPa)	σ after 24 hours (kPa)	Stress decrease (%)	UCS_r (kPa)	UCS_r/UCS
LF	38	3	92	201	0.99
LF	74	5	93	206	1.01
LF	90	7	92	197	0.97
LF	136	8	94	181	0.89
LF	187	11	94	163	0.80
LN	43	5	88	240	0.96
LN	81	10	86	238	0.95
LN	104	13	88	249	0.99
LN	162	15	91	227	0.91
LN	219	22	90	211	0.84
HF	425	44	90	953	1.02
HF	578	52	91	914	0.98
HF	701	77	89	866	0.92
HF	793	110	86	815	0.87
HF	842	151	82	772	0.82
HN	364	45	87	1090	1.01
HN	512	87	83	1113	1.03
HN	680	99	85	1076	0.99
HN	794	160	80	1018	0.94
HN	907	218	76	943	0.87

Note: UCS_r: uniaxial compressive strength value after relaxation, UCS: Uniaxial compressive strength of specimens having no relaxation, σ_i: stress level at the initiation of the relaxation

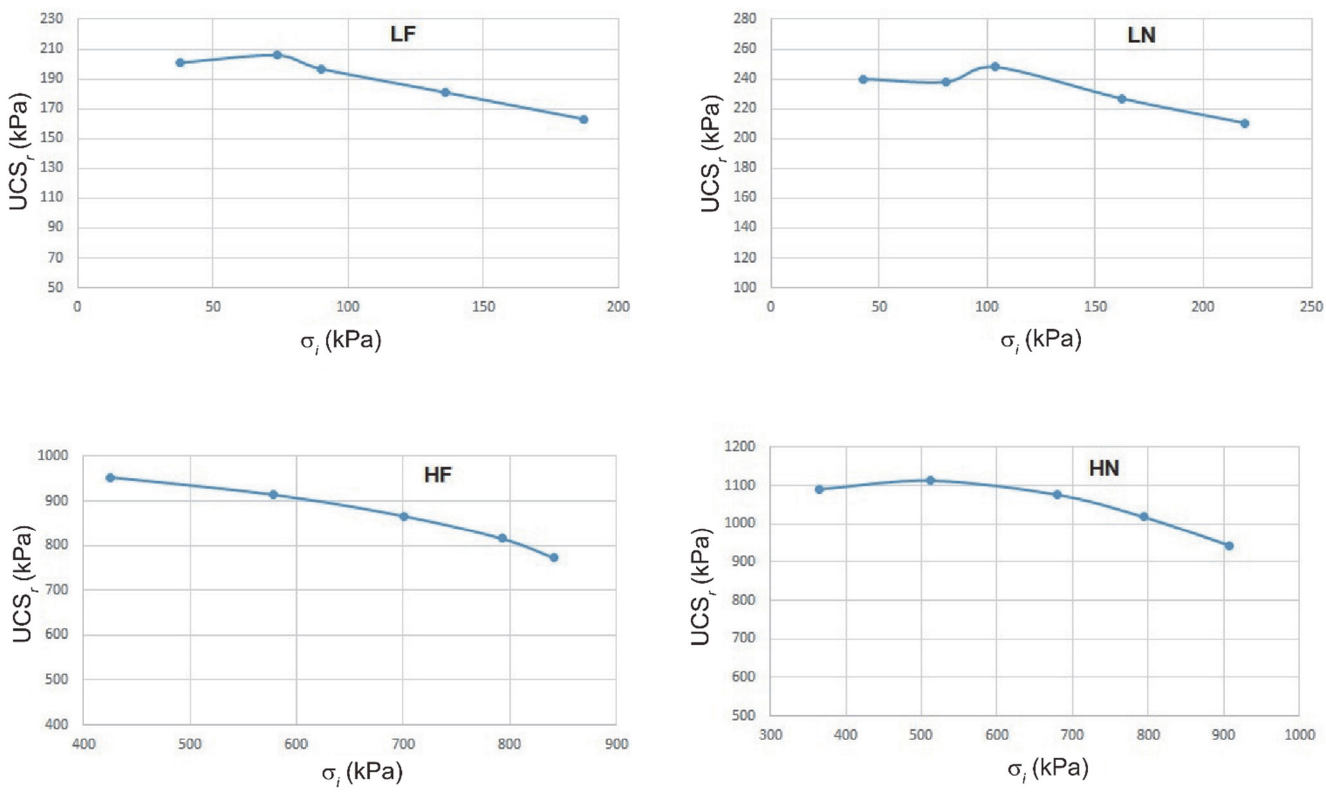


Fig. 5 Variations in uniaxial compressive strength values after relaxation (UCS_r)

4. DISCUSSIONS AND CONCLUSION

The stress relaxation event occurs due to gaining plasticity owing to an external load on the strained material. As the strain energy level increases, it is expected to also have an increase in gaining plasticization and time for completion of it (Li *et al.* 2013; Lade and Karimpour 2016; Komurlu 2021). The stress relaxation was assessed to be relatively rapid, especially in early times. Results of other relevant studies are parallel to those obtained from this study that the stress relaxation rate decreases with an increase in time (Augustesen *et al.* 2004; Tong and Yin 2013; Bagheri *et al.* 2019). For natural soils without a binder additive, time for completion of the relaxation increases and the rate of the relaxation decreases due to the fines content (Yin *et al.* 2014; Levin *et al.* 2019; Li *et al.* 2022). However, the fines content was determined to increase the relaxation rate in the case of using cement binder.

The binder usage makes the material properties of soils different. As the surface area of particles increases, the cement contacted surface percentage decreases with a decrease in the particle size. Therefore, the fines content can have a negative effect on strength values of the cemented soils, as confirmed by outcomes of this study (Park and Choi 2011; Moon *et al.* 2020; Gu *et al.* 2022). This situation is estimated to be the reason for the relatively higher rate of relaxation and low strength loss resistivity against the relaxation of specimens with fines content. As the cement content increased, the difference between the strength values of samples with and without the fines content increased. The N coded samples without the fines content have already a proper gradation in consideration of the C_u and C_c coefficient values of 12.6 and 1.5, respectively (ASTM D2487-17; Uzuner 2007). With increasing cement content, the relaxation rate decreased and the relaxation completion time increased. According to the results, the cement content improves the resistivity against the strength loss due to the relaxation effect.

This study is a laboratory scale study. Even though the CSS is a well-studied material used in different geotechnical engineering works, research on stress relaxation is limited. It is beneficial to investigate the relaxation topic for various service life times of the CSS mixes. To investigate the stress relaxation effect on the service lifetime property, there are various research topics like environmental conditions, characterization for industrial applications, mixing CSS with various additives, mechanical behaviour under the triaxial loading condition, shear characteristics, bearing capacity effect for foundations, settlements in roads, *etc.* (Cong *et al.* 2020; Nafisi *et al.* 2021; Wang *et al.* 2021).

The stress relaxation effect was found to be non-ignorable for time-dependent strength variations of the CSS. As confirmed by this study, the relaxation should be taken in consideration in geotechnical engineering designs. In particular, stress levels over 80% of the specimen strength value have been evaluated to cause significant time-dependent changes in their bearing capacities. This study is aimed to contribute to future studies on time-dependent strength variations of the CSS materials. To better understand the stress relaxation properties of the CSS mixes, there are numerous topics to investigate within the future works. For instance, effect of particle size distribution, water content, binder type, environmental conditions, mixing and compaction details and some other parameters can be investigated in new studies on the stress relaxation and time-dependent strength losses of the CSS mixes.

According to the results obtained from this study, following research findings can be noted as conclusion matters:

1. The stress relaxation rate decreases with an increase in the loading period.
2. Strength values of the CSS specimens can significantly decrease due to the relaxation effect in case of high initial stress (σ_i) values.
3. Duration for completion of the stress relaxation increases with an increase in the cement content.
4. An increase in the cement content improves the UCS values after the stress relaxation effect.
5. The fines particle content decreases the strength loss resistivity of the CSS mixes against the stress relaxation effect. UCS values of CSS mixes with the fines content can even be lower than σ_i value after the relaxation period.

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DATA AVAILABILITY

The data and/or computer codes used/generated in this study are available from the corresponding author on reasonable request.

CONFLICT OF INTEREST STATEMENT

The authors state that there are no financial interests or personal relationships that might influence the work reported in this paper. The authors declare that there is no conflict of interest.

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