

Article

The Effect of Scrap Tires and Reclaimed Asphalt Pavement on the Behavior of Stone Columns

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Abstract: The objective of this investigation is to understand how to use waste tires to surround stone pillars and mix gravel with recycled asphalt pavement (RAP) and stone pillars to provide an environmentally friendly and cost-effective weak layer improvement method. To study the behavior of such stone columns, experiments were conducted in units consisting of a single stone column with recycled asphalt pavement as filling material and a single stone column covered with old tires. To test the effect of different mixing ratios, rapeseed content was selected from 0% to 100%. Elasticity tests were conducted on clad and nonclad stone column samples. Furthermore, direct shear tests were conducted on samples with different ratios of gravel and rapeseed mixtures. The results of the load-bearing capacity test show that the cover of the stone columns with old tires can significantly increase the load-bearing capacity. Replacing 25% of natural stone column aggregates with RAP increases the load capacity. But as the percentage of RAP in the mixture increases from 25% to 100%, the loading capacity decreases. Another advantage is the reinforced stone column. From the point of view of ecology, an advantage is the use of recyclable materials.

Keywords: environmental; tire scrap; reclaimed asphalt pavement; stone column; loading capacity; shear strength



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1. Introduction

In recent years, environmental problems resulting from the disposal of scrap tires have become a global issue, and the need to reuse them in new applications has increased. The unique properties of tires such as low density, hydrophobicity, high strength, and durability have expanded these applications in various engineering fields [1]. Geotechnical engineering has great potential to reuse these materials [2].

On the other hand, due to the breakdown of asphalt surfaces, in many cases these materials are scratched off the road surface and stored around the road; therefore, these materials will occupy significant areas of valuable land. The use of reclaimed asphalt pavement (RAP) instead of clean gravel is a sustainable solution to reduce environmental concerns about natural resource limitations and waste recycling. Although in many countries all asphalt is used for road recycling, in many additions this is not the case.

The stone column is one of the most cost-effective soil improvement techniques in which typically 15–20% of the weak soil is replaced by natural aggregates [3]. Stone columns are compressive shafts, hence having high compressive strength with low tensile strength and, therefore, carrying a larger portion of the applied load and causing smaller deformation in the soil. Stone columns increase the bearing capacity of soft soil and reduce its settlement [4]. Various research has been carried out in the experimental field of stone column modeling. Ambily and Gandhi [5] investigated the load-settlement behavior of single and group stone columns using an experimental model of units of cells. Fattah et al. [4] applied clay beds in a large box to reduce the boundary effect on the modeling of the stone column.

A sustainable way to bury waste materials such as recycled asphalt pavement (RAP) and scrap tires is to use them to replace natural aggregates in stone columns.

Many researchers have successfully tested the performance of some waste materials for replacement with stone column aggregates as an environmentally friendly method during experimental investigations. Marto et al. [6] showed that using bottom ash, coal-burning waste, as an alternative to stone column aggregates improved its shear strength. Ayothiraman and Soumya [7] replaced different percentages of stone column aggregates with tire shards and found that 20% tire shard increases the bearing capacity of the stone column by 36%. Then, Shariatmadari et al. [2] used tire shreds in three fine, medium, and large sizes in stone columns, and in addition to bearing capacity, shear strength, and permeability were investigated. The results indicated that 20% of medium tires, which are the same size as stone column aggregates, increase the bearing capacity and internal friction angle by 30% and 5%, respectively, without changing the permeability.

Different failure mechanisms can occur in the stone columns under loading. Barksdale et al. [8] described three types of failure in the stone column: shear failure, punch failure, and bulging failure. These failure mechanisms have been studied by many researchers [9,10].

According to Wong's research [11], if a stone column is frictional or if the end bearing ultimately fails under the bulging if it has a length-to-diameter ratio greater than three, the geotextile sheet encasement is used to reduce the effect of bulging and, subsequently, to increase the bearing capacity of the stone column. Afshar and Ghazavi [3], using geotextile sheets as horizontal and vertical reinforcement throughout and at half the length of the stone column, indicated that geotextile reinforcement increases the bearing capacity of the stone column and reduces the bulging effect.

Miranda et al. [12] compared load transfer to stone columns encased by two types of geotextiles to illustrate the effect of different geotextiles on the performance of the stone column. In addition to confining the stone column with geotextiles, Debnath and Dey [13] used a reinforced sand blanket with geogrid sheets to enhance the load transfer to the stone column and increase drainage speed. Their results showed that this method has a significant effect on improving the bearing capacity of the stone column.

Several researchers have gone further and investigated the effect of replacing stone column aggregates with waste materials and stone column encasements with geotextiles. Prasad et al. [14] showed that using silica manganese slag as a substitute for stone column aggregates and geotextile encasement could increase the bearing capacity of the stone column by 47%. Mazumder et al. [15] also showed that by encasing a stone column with a geogrid and replacing more than 40% of its aggregates with tire shreds, the bearing capacity increased by more than 100%. Other studies have also shown the advantages of using pneumatics in this segment [16].

This study aims to present an environmentally friendly and cost-effective improvement method for weak soils in which scrap tires and RAP waste materials are used as encasement and filler materials in stone columns, respectively.

2. Materials

2.1. Soil and Stone Column Material

Stone columns are ideally suitable for improving clays, soft silts, and loose silty sands [8]. Clay soils with an undrained shear strength between 7–50 kPa can be improved by the stone column method. The properties of selected clay surrounding the stone column are listed in Table 1.

Table 1. Properties of clay.

Parameters	Value	Specification
Liquid limit (%)	28	ASTM D4318-00 [17]
Plastic limit (%)	20	ASTM D4318-00 [17]
Plastic index (%)	8	ASTM D4318-00 [17]
Optimal moisture content (%)	17	ASTM D698-00 [18]
Maximum dry density (kN/m ³)	17	ASTM D698-00 [18]
Bulk density at 25% water content (kN/m ³)	18	-
Undrained shear strength (kPa)	7	ASTM D2166-00 [19]
USCS classification symbol	CL	ASTM D2487-06 [20]

A series of unconfined compressive strength tests were carried out on a cylindrical sample with a diameter of 38 mm and a height of 76 mm to obtain the moisture content corresponding to the undrained shear strength of 7 kPa. The clay moisture content was obtained at 25%, and this amount was kept constant in all unit cell tests.

RAP aggregates with a maximum particle size of 10 mm and the same clean aggregates used for the production of asphalt with particle sizes ranging from 2–10 mm were used as natural aggregates. More samples were taken by replacing 0, 25%, 50%, 75%, and 100% by weight of clean aggregates with RAP. Each sample is named RAPX, where X represents the percentage of RAP in the sample. For example, RAP25 is a sample with 25% RAP and 75% clean aggregate. The aggregate samples that were prepared and their properties are shown in Figure 1 and Table 2. The particle size distribution for stone column materials is depicted in Figure 2.

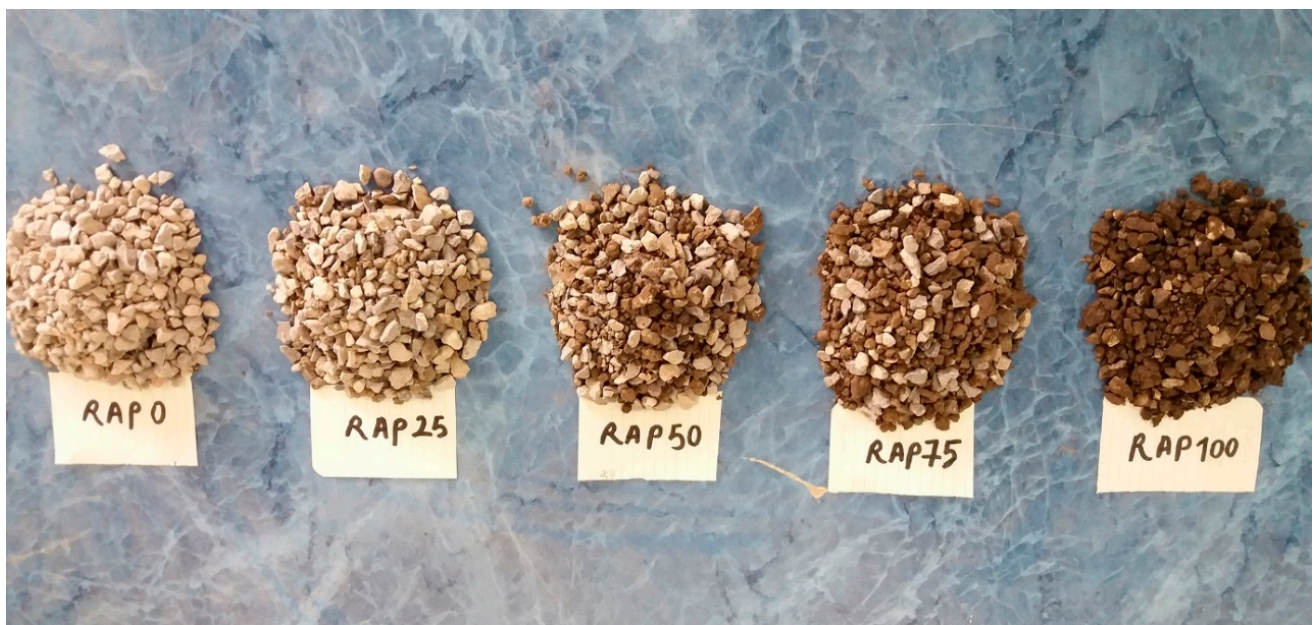
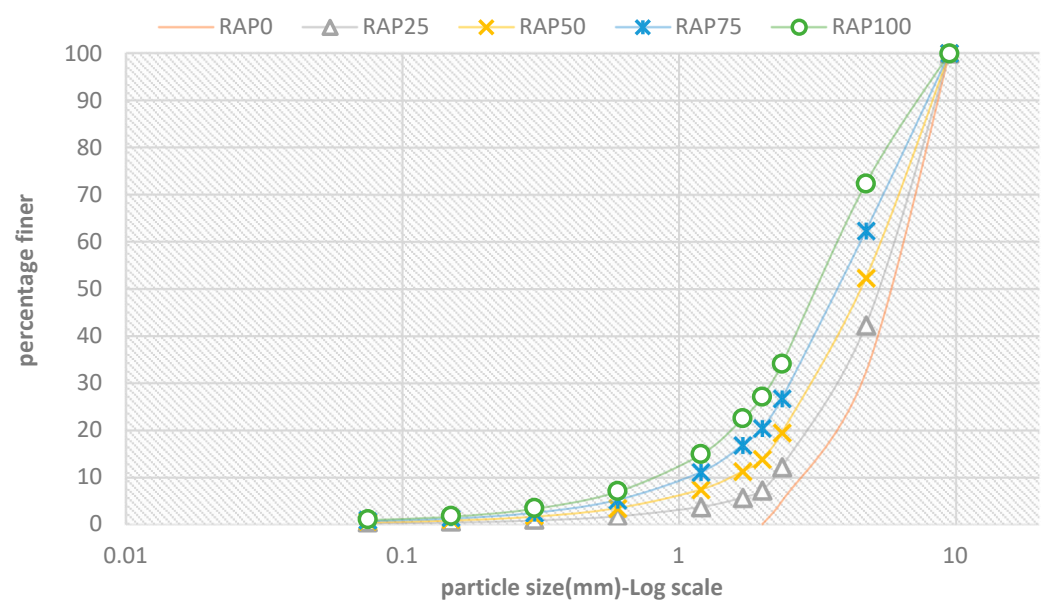
**Figure 1.** Prepared aggregate samples [21].

Table 2. Properties of prepared aggregate samples [21].

Specification	Value					Specification
	RAP100	RAP75	RAP50	RAP75	RAP0	
Maximum dry density (kN/m ³)	17.23	17.23	16.98	16.95	16.58	ASTM D4253-00 [22]
Minimum dry density (kN/m ³)	14.85	14.71	14.56	14.52	13.95	ASTM D4254-00 [23]
Matrix density for a test at 70% relative density (kN/m ³)	16.44	16.39	16.17	16.14	15.69	-
Uniformity coefficient (Cu)	2.3	2.9	3.4	4.3	4.3	ASTM D2487-06
Curvature coefficient (Cc)	1.10	1.07	1.18	1.12	1.40	ASTM D2487-06
USCS classification symbol	GP	GP	SP	SP	SP	ASTM D2487-06

**Figure 2.** Particle size distribution for stone column materials.

In the aggregate sample preparation process, natural aggregates and RAP content are selected to achieve a target relative density of 70% for all samples. For each mixture, the minimum and maximum densities are calculated according to ASTM D4253 and D4254, and the unit weights of the matrix are obtained by Equation (1).

$$D_r = \left(\frac{\gamma_{d \text{ matrix}} - \gamma_{d \text{ min}}}{\gamma_{d \text{ max}} - \gamma_{d \text{ min}}} \right) \left(\frac{\gamma_{d \text{ max}}}{\gamma_{d \text{ matrix}}} \right) \quad (1)$$

where D_r is the relative density and $\gamma_{d \text{ matrix}}$ denotes the dry density of the matrix. $\gamma_{d \text{ max}}$ and $\gamma_{d \text{ min}}$ refer to the maximum and minimum dry densities of the mixtures, respectively.

2.2. Tires

The tires used in this study have a 160 mm outer diameter, 78 mm inner diameter, and 50 mm width. These model tires were made of the same rubber materials used in actual tires, and there are carcass plies and beads in their structure.

3. Tests

3.1. Loading Capacity Test

In this investigation, a testing ring with a capacity of 30 kN was used to load the unit cell. The load was applied at a constant strain rate of 1 mm/min. A cylindrical tank with a diameter of 228 mm, a height of 330 mm, and a thickness of 25 mm was used as a unit cell

tank, and a rigid steel plate with a diameter of 220 mm and a thickness of 20 mm was used as a loading plate.

Cell loading tests were conducted, including loading tests on unreinforced clay and loading tests on bare cladding and tire-clad stone columns with different aggregate mix ratios. In all tests, a tire inner diameter of 78 mm and a length of 300 mm for all posts were assumed. Therefore, the ratio of length to diameter of the stone pillar is 3.85. Therefore, according to the study of Wong [11], in this study, the control of stone pillar protrusions failed.

In all tests, the inner walls of the test jars were coated with a thin layer of grease before the clay was poured into the jars to minimize the impact of friction between the clay and the walls of the jar on the test results. For unreinforced clay units, the clay bed was prepared in one layer with a thickness of 30 mm and six layers with a thickness of 50 mm each. To achieve a uniform density over the clay layers, each layer was compacted using a round steel tamping machine with a mass of 7.5 kg. To prepare a clay bed with a moisture content of 25%, corresponding to an undrained shear strength of 7 kPa, the natural moisture content of the clay was first determined and additional moisture was added to the clay to achieve a moisture content of 25% packed in a double layer thick nylon bag.

Bare stone columns were constructed using thin-walled open-ended steel tubes with an outer diameter of 78 mm and a wall thickness of 0.7 mm. To facilitate the penetration and removal of the pipe into the ground without affecting the surrounding soil, the inner and outer surfaces of the pipe were coated with a thin layer of grease. After pouring the clay in a 30 mm thick layer at the bottom of the tank, the pipe was placed in the middle of the tank and then the clay was poured in a 50 mm thick layer until the tank was full. Each layer was compacted using a circular steel tamper with a mass of 2.5 kg and a diameter of 50 mm to achieve the required density. The amount of aggregates required to form the stone column was calculated based on the bulk densities required shown in Table 2 for each mixture and loaded into the pipe in layers 50 mm thick. The compaction of the stone column was carried out using a circular steel tamper with a mass of 2.5 kg and a diameter of 50 mm to achieve a uniform density in each layer. To facilitate the removal of the pipe from the soil after completion of the stone column, the pipe was gradually pulled from the soil by 40 mm after preparing each layer.

For the construction of the tire-encased stone column, instead of using the pipe, the space needed to pour the aggregates was created by placing the tires on each other. For this purpose, six tires were placed on each other to form a 300 mm long stone column. After pouring the clay into the tank in a 30 mm thick layer, the first tire was placed in the center of the tank and the next 50 mm thick clay layer was poured surrounding the tire. Then, this process continued until the sixth tire was put in the tank and the last layer of clay was poured around it. For the construction of the stone column, the aggregates were poured into the central space of the tires in 50 mm thick layers according to the matrix densities shown in Table 2 and then compacted. It should be noted that due to the difficulty in accessing the tires after they were placed in the tank, the space inside each tire was filled with aggregates before being placed in the tank according to the desired matrix densities.

Each unit cell was kept in the laboratory for 24 h before the loading test to ensure uniform moisture between the different layers of clay. During this time, the outer surface of the tank was covered with a double layer of thick nylon bags to prevent moisture loss. The moisture content of the clay was obtained before and after the loading test, and its variation was in the range of 1.5%. Each loading test was stopped at 32 mm displacement, and the load was read at every 1 mm displacement. It should be noted that due to the fast loading, the test condition was considered to be undrained. A typical test arrangement for a tire-encased stone column test is shown in Figure 3a,b.

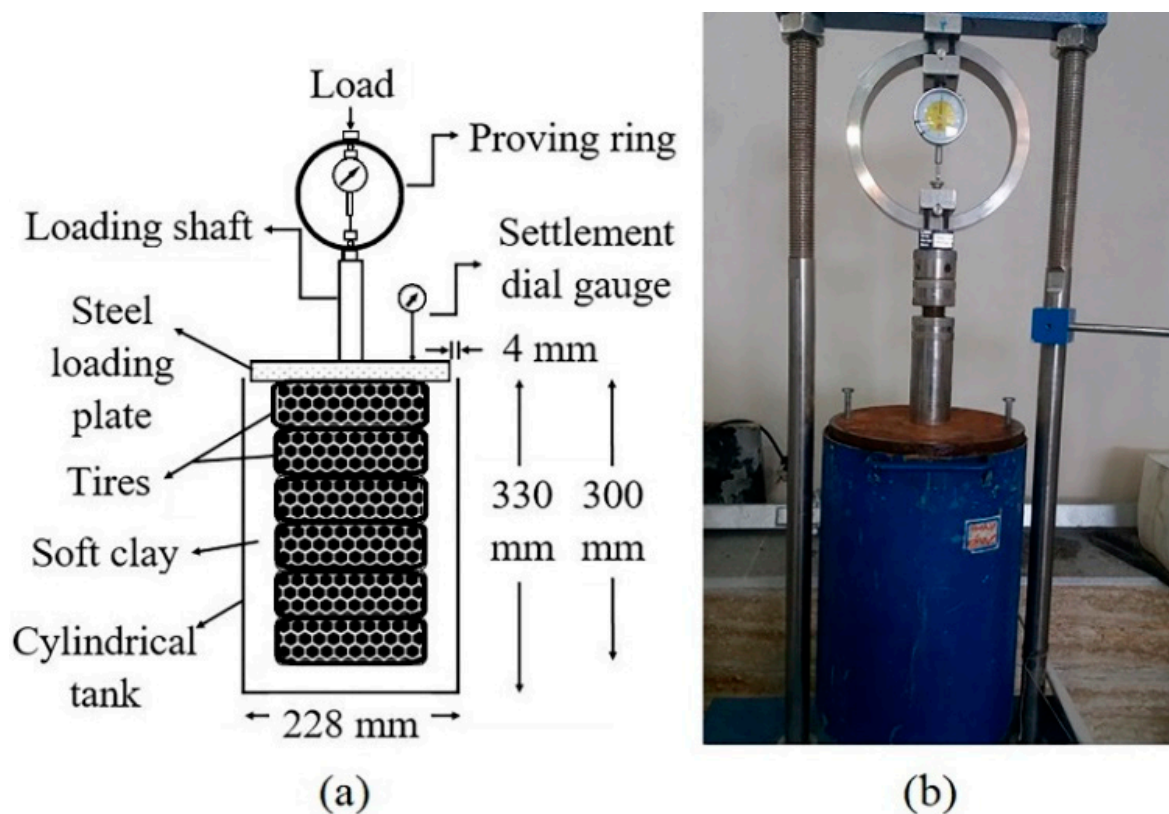


Figure 3. Typical test arrangement for a tire-encased stone column test: (a) sketch; (b) photograph.

3.2. Direct Shear Test

Different direct shear tests were carried out on RAP0—RAP100 mixtures according to ASTM D3080 [24] in a large-scale direct shear device with dimensions of 30 cm × 30 cm × 15 cm. To compact the mixture to the densities of the target matrix, a metal hammer with dimensions of 10 cm × 10 cm was placed on the surface of the aggregates and hit with a rubber hammer. Direct shear tests were carried out at normal stresses of 100, 200, and 300 kPa. It should be noted that these normal stresses are approximately selected due to the vertical force that the aggregates have experienced in the loading capacity test. A shear rate of 1 mm/min was selected according to ASTM D3080, and with each millimeter added to the horizontal displacement, the vertical displacement and the shear force were measured. The test was stopped when the shear force was constant or the horizontal displacement reached 10% of the shear box width (30 mm).

4. Results and Discussion

4.1. Charge Capacity

The load-settlement behavior of non-encased and tire-encased stone columns with different mixing ratios is shown in Figures 4 and 5, respectively. By comparing these figures, it can be seen that the slope of the curve corresponding to the non-encased stone column decreases by applying load steps and approaches to a vertical asymptote at the 32 mm settlement, indicating that the ultimate failure occurs in the stone column. On the contrary, the behavior of the tire-encased stone column does not fail at the 32 mm settlement because the slope of the curve does not approach the vertical asymptote, and, hence, the ultimate bearing capacity of the tire-encased stone column increases. The cause of this difference in behavior may be related to the mechanical properties of the rubber used in the tires.

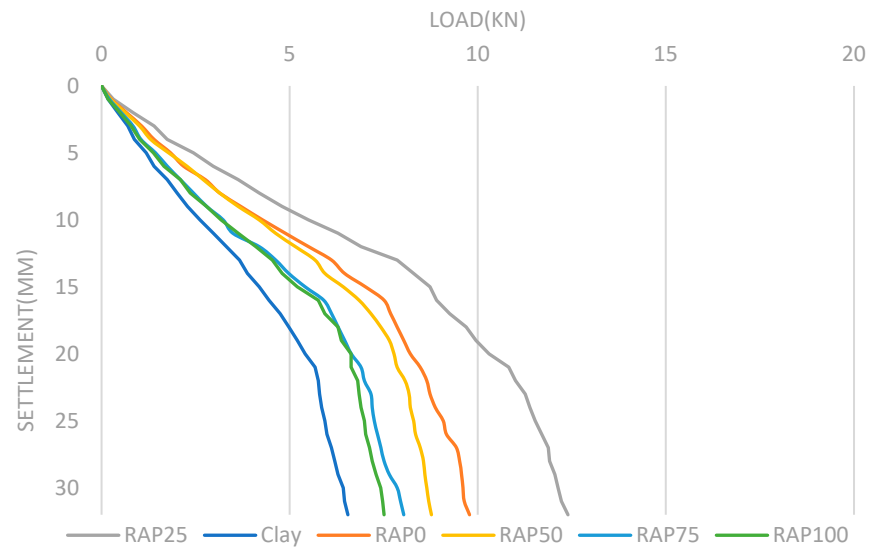


Figure 4. Load-settlement behavior of non-encased stone columns with different mixing ratios.

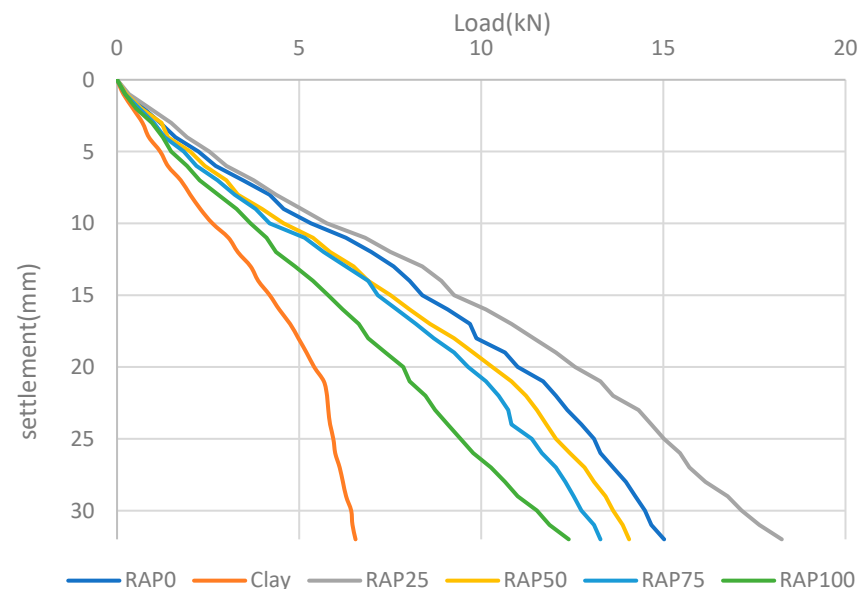


Figure 5. Load settlement behavior of tire-encased stone columns with different mixing ratios.

In the stone column encased in a tire, the tire is compressed as the loading continues. Each tire is subjected to different stresses including vertical pressure of the above tire, horizontal stress from the surrounding clay, horizontal stress from the stone aggregates, and frictional stresses. The horizontal stress of the stone is applied to the inner wall of the tire in the opposite direction to the stress of the surrounding clay. Because the deformation of the stone column and the soft clay is almost the same, the stiff stone column must carry a greater part of the load than the soft clay [8]. Therefore, the resultant force is positioned horizontally outward and causes horizontal tensile stress on the tire. Baranowski et al. [25] performed tensile and compression tests on rubber coupons from car tires and showed that with increasing strain, tensile and compressive stresses increased in the tire. Thus, increasing tire settlement and deformation causes an increase in mobilized compressive and tensile stresses in the tire, i.e., the tire plays a greater role in load bearing. Consequently, when the settlement in the tire-encased stone column increases, the bearing capacity increases at the same rate rather than decreasing the loading rate and approaching the vertical asymptote at the end of the test. Therefore, encasing the stone column with tires,

in addition to increasing the bearing capacity and preventing bulging, causes the stone column to fail at greater settlement.

Table 3 shows the improvement factor for all samples. The improvement factor is defined as the ratio of the maximum load capacity of the stone column with RAP aggregates to the bearing capacity of the non-encased stone column with natural aggregates, RAP0 [2]. In this table, the letter E beside the symbol represents the encased sample.

Table 3. The factor of improvement of the non-encased and tire-encased stone columns.

Symbol	Factor of Improvement	Symbol	Factor of Improvement
RAP0	1	ERAP0	1.54
RAP25	1.27	ERAP25	1.87
RAP50	0.90	ERAP50	1.44
RAP75	0.82	ERAP75	1.36
RAP100	0.77	ERAP100	1.27

According to Table 3, regardless of whether the stone column is tire-encased or not, the RAP content in the samples changes the factor of improvement. The sample with a 25% RAP content has a higher factor of improvement than other mixing ratios. By increasing the RAP content to more than 25%, the factor of improvement has decreased. Tire-encased stone columns have an improvement factor greater than one, regardless of the percentage of RAP content. Mixing RAP with natural aggregates changes the gradation of aggregates. As shown in Figure 2, the percentage of fine grains increased with increasing RAP content in the mixture. Ghanizadeh et al. [26] showed that gradation is an important factor that affects the mechanical properties of natural and RAP aggregate mixtures. As a result, the loading capacity is affected by the gradation of the mixture. There are many voids in the structure of poorly graded aggregates due to the lack of many sizes in the gradation. The presence of these spaces interrupts the transfer of force between the particles and therefore reduces the loading capacity [27]. Poorly graded aggregates are commonly used for stone column filling materials to improve drainage speed [3,7,12]. In this study, by replacing 25% of the stone column material with RAP aggregates, according to Figure 2, approximately 7% of the sand aggregate was smaller than 2 mm (minimum size of natural aggregates) and, generally, 10% of the sand aggregate was added to the matrix. These fine particles fill the spaces between the coarse particles and increase the bearing capacity of the stone column by increasing the locking between the coarse particles and completing the force transmission paths. Therefore, the loading capacity of the stone column is increased by replacing 25% of the natural aggregates with RAP. However, as the percentage of RAP increases from 25% to 100%, the percentage of sand aggregates increases according to Table 2. The type of soil is not classified as gravel soils. This change in gradation reduces the load capacity of the stone column. According to Table 3, the use of RAP100 reduces the bearing capacity of the stone column to 77% of the bearing capacity of the stone column made of natural materials. The 23% reduction in bearing capacity is not significant, and, therefore, the use of RAP100 is reasonable and justifiable. In other words, a stone column made of 100% or any percentage of RAP can be used without a significant reduction in bearing capacity.

Figure 6 illustrates the effects of the percentage of RAP aggregates and the rubber encasement of the stone column on the bearing capacity. The gentle slope of the curve for the RAP content greater than 50% indicates that increasing the percentage of RAP does not significantly decrease the loading capacity of the stone column. Furthermore, the significant effect of the tire encasement of the stone column can be seen in Figure 6.

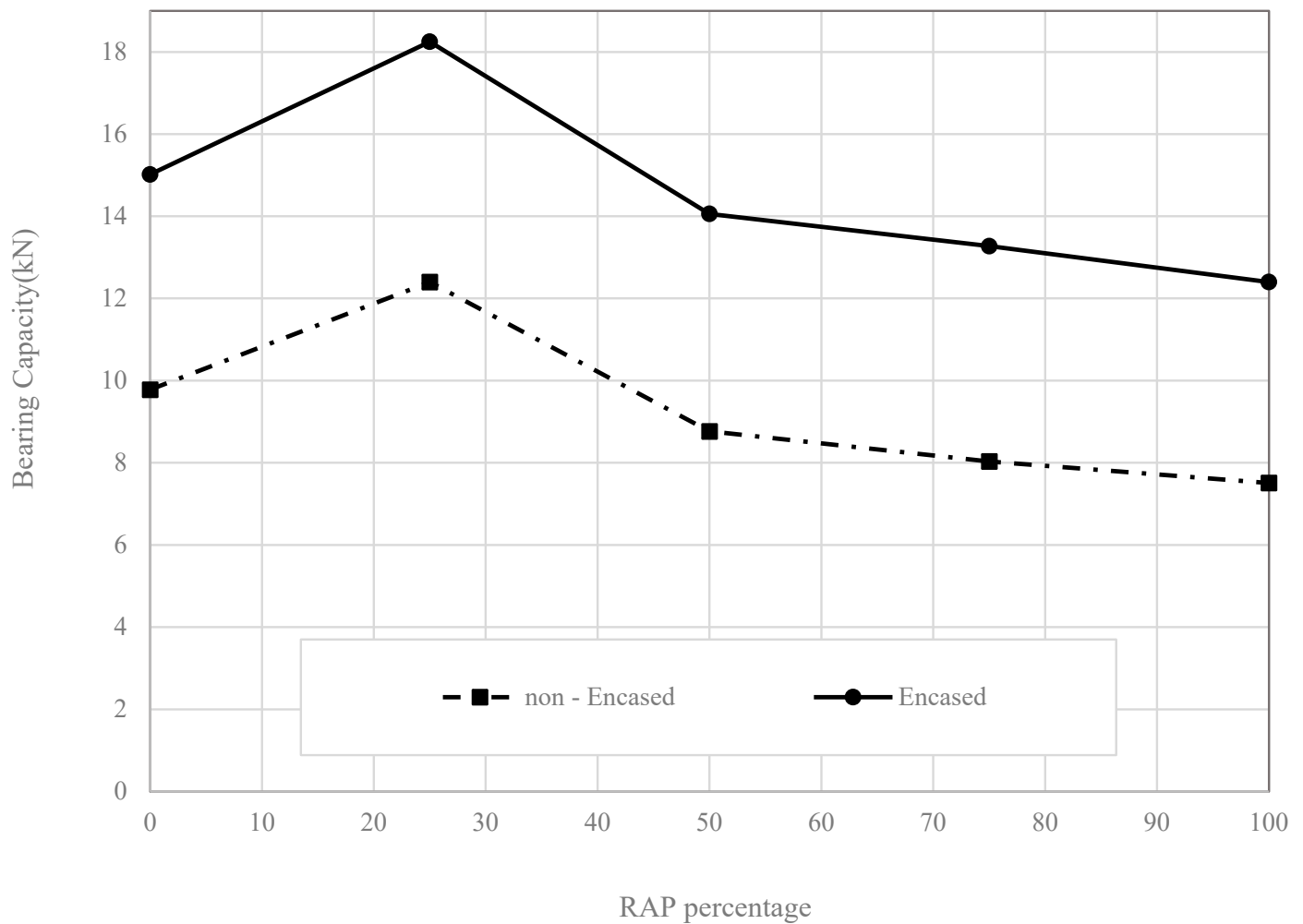


Figure 6. Bearing capacity of non-encased and tire-encased stone column vs. RAP percentage.

The load ratio (LR) is one of the parameters that can be used to determine the efficiency of stone columns in terms of loading capacity [3]:

$$L.R = \frac{\text{load obtained from stone column reinforced soil}}{\text{load obtained from soft soil without stone column}} \quad (2)$$

In Figures 7 and 8, the $L.R$ variation with the settlement is shown for the non-encased and tire-encased stone columns, respectively. The maximum and minimum $L.R$ correspond to RAP25 and RAP100, respectively. It is observed that confining the stone column with the tires improves the $L.R$ and also changes load-settlement behavior. In non-encased stone columns, the slope of the $L.R$ curve increases in small amounts of settlement and then decreases by increasing the amount of settlement to more than 15 mm due to the approaching failure state of the stone column. However, in the tire-encased stone column, the $L.R$ value increases from the beginning to the end of the test due to the tire confinement. Mobilized tensile and compressive stresses in tires improve the slope of the $L.R$ curve and also prevent bulging failure in the stone column.

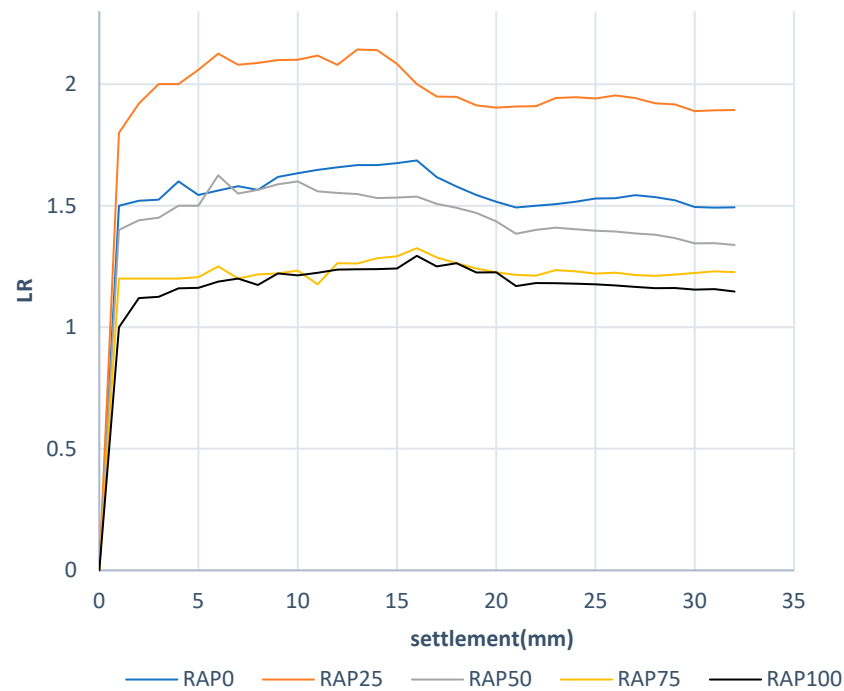


Figure 7. Smoothed curve of LR–settlement of non-encased stone columns.

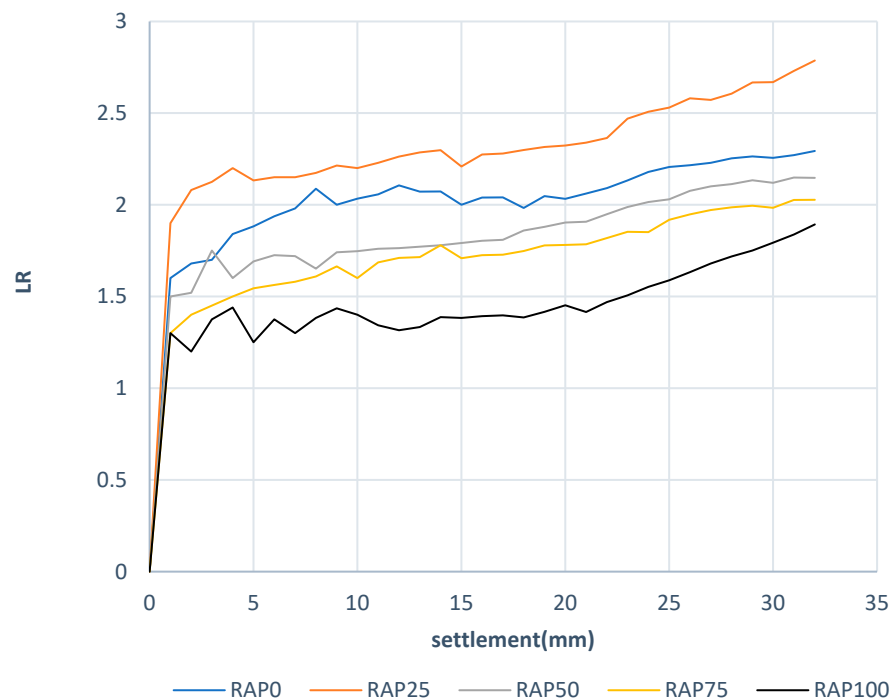


Figure 8. Variation of load ratio versus settlement of tire-encased stone columns.

4.2. Shear Strength

Figure 9 shows the Mohr–Coulomb curves of the RAP0 to RAP100 samples, and Table 4 shows the values of the internal friction angle and cohesion of the samples. According to Table 4, there is a meaningful relationship between the percentage of RAP in the sample and the strength parameters of the angle of internal friction and cohesion. The variation of the internal friction angle and the cohesion normalized to the corresponding values of RAP0 versus the percentage of RAP is shown in Figure 10. As can be observed with increasing RAP percentage in the sample, the internal friction angle decreases while the cohesion increases. However, there is no significant change in the friction angle and cohesion of

the samples to avoid using samples with a high percentage of RAP. Samples with a high percentage of RAP, as can be seen in Table 4, have a high friction angle (minimum 39.2°) and even higher cohesion than samples with a lower RAP.

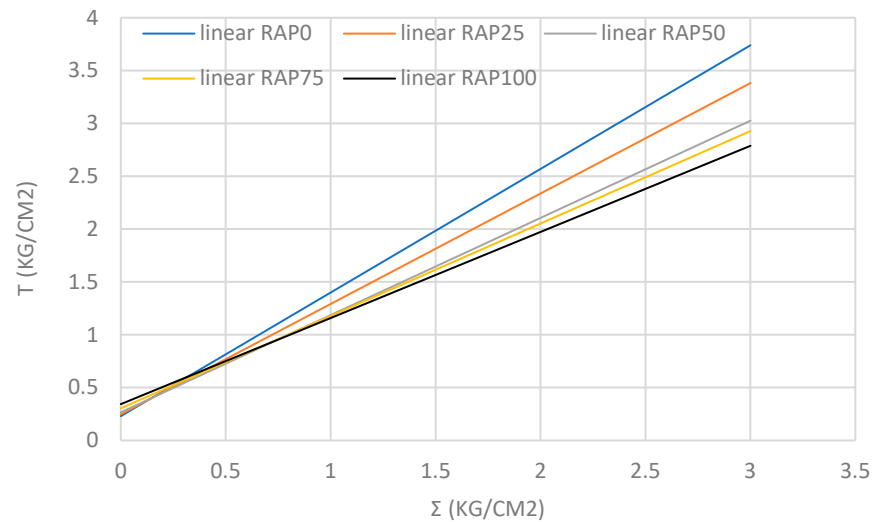


Figure 9. Mohr–Coulomb curves for different mixtures.

Table 4. Mechanical parameters of different mixtures.

Sample	Φ (°)	C (kPa)	Normalized ϕ	Normalized C
RAP0	49.5	22.56	1	1
RAP25	46.3	24.52	0.93	1.09
RAP50	42.6	26.49	0.86	1.17
RAP75	41.2	29.43	0.83	1.30
RAP100	39.2	33.35	0.79	1.48

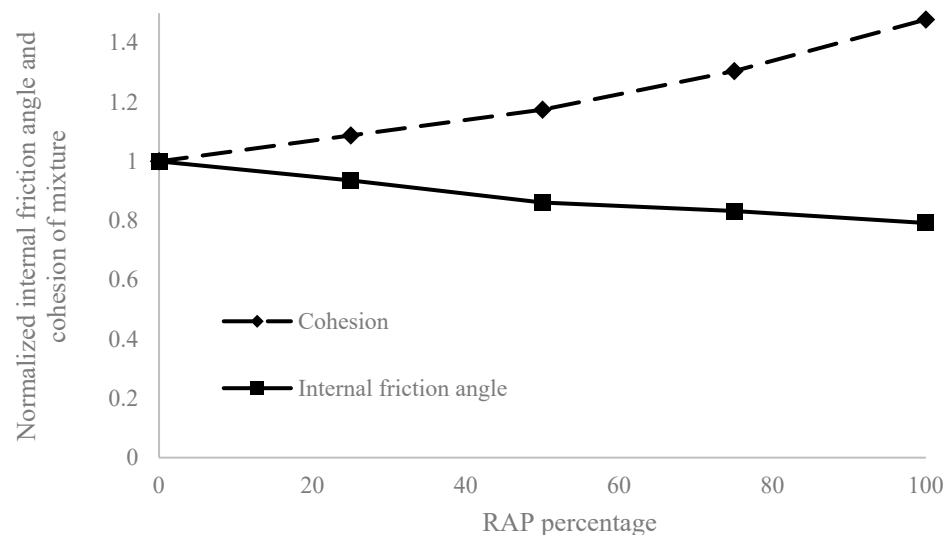


Figure 10. Normalized internal friction angle of cohesion of different mixtures.

The reduction in friction angle and the increase in cohesion may be due to an increase in the percentage of asphalt, the presence of sand with smaller particles in the aggregates of the samples, and the change in the gradation of the aggregates.

Aggregates reduce the friction between particles and, by smoothing their surfaces, facilitate particle movement when subjected to shear force. Thus, the RAP content in the sample reduces the mobilized friction force between the particles and, consequently, the internal friction angle decreases.

The stress-strain behavior of the direct shear test for vertical loading of 200 kPa is shown in Figure 11. According to Figure 11, as the percentage of RAP increases, shear failure of the mixture occurs at a greater displacement. By drawing a line parallel to the horizontal axis, it can be observed that, at constant shear stress, the shear displacement increases with increasing RAP content. As a result, increasing the percentage of RAP causes ductile behavior in the mixture.

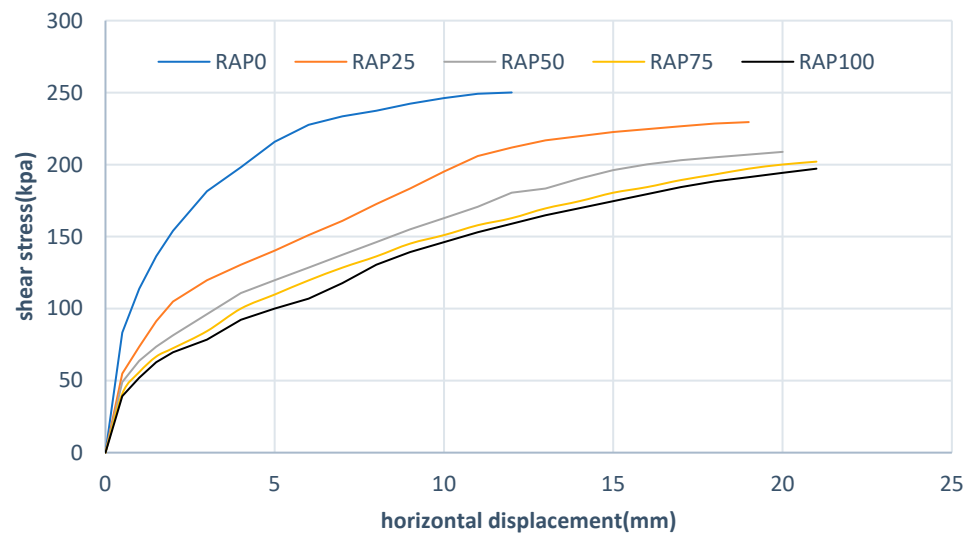


Figure 11. The stress-strain behavior of different mixtures.

5. Conclusions

In this study, to improve the mechanical properties of soft soils, an environmentally friendly and cost-effective improvement method was presented. In this method, scrap tire and RAP waste materials are used as encasement and filler materials in stone columns, respectively. To increase the bearing capacity of the stone column and to reduce the effects of bulging, small tires were used with the same rubber as the tires to confine the stone column, and the effect of the encasement of tires on the bearing capacity of different mixtures was investigated. The effect of RAP as an alternative to natural aggregates of the stone column was investigated. For this purpose, RAP was replaced by natural aggregates with weight percentages of 0, 25, 50, 75, and 100%. Unit cell loading tests and large direct shear tests were carried out to study the effect of the inclusion of RAP aggregates on the mechanical properties of the stone column.

The confinement of the stone column with tires increases the factor of improvement to more than one, indicating that the encasement of the tires significantly increases the loading capacity of the stone column.

Increasing the settlement and tire strains causes an increase in the mobilized compressive and tensile stresses in the tire; therefore, the tire plays a greater role in load bearing. Consequently, as the settlement in the tire-encased stone column increases, the bearing capacity increases.

The shear strength and loading capacity of the stone column depends on the percentage of RAP aggregates in the mixture. Replacing 25% of natural stone column aggregates with RAP increases the load capacity. But as the percentage of RAP in the mixture increases from 25% to 100%, the loading capacity decreases. A series of unit cell tests have been carried out to investigate the effects of replacing stone column aggregates with RAP aggregates and using tires as encasing elements on the load-settlement characteristics of stone columns. The unit cell consists of a cylindrical clay bed with a stone column in its center. To compare

the performance of stone columns with different mixing ratios, RAP contents of 0%, 25%, 50%, 75%, and 100% are selected. Furthermore, the effect of adding RAP on the shear strength properties of the stone column has been investigated using a series of large-scale direct shear tests on different samples.

The contribution to knowledge is in the expansion of practical knowledge when applying the procedures presented within the framework of the utilization of waste material, specifically pneumatics. With regard to the typified input assumptions mentioned here, the results are suitable for future applicability in practice. This article also provides several relevant insights for future research.

Author Contributions: H.B. Formal analysis, Writing—original draft, Data curation. M.J.S.: Visualization, Methodology, Software. B.B.: Conceptualization, Project administration, Resources. P.L.: Supervision, Writing—review and editing, Funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available in the article.

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Conflicts of Interest: The authors declare no conflicts of interest.

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