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Original Article

A Sustainable Solution for Vertically and Horizontally Reinforced Stone Columns

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Abstract - *Stone columns are a widely used technique for soil reinforcement. In extremely soft ground situations, individual stone columns within a geosynthetic enclosure would help preserve the stones from squeezing into the surrounding soil. This article presents an opportunity to demonstrate the necessity of using various recycled aggregates in lieu of natural aggregates as a solution to the exploitation of natural aggregates and the disposal of construction waste. The feat of geotextiles as smart material in the construction of Geotextile Encased Stone Columns has been evaluated through laboratory modeling on the California Bearing Ratio (CBR) mould through a unit cell approach. Different aggregates' load-settlement characteristics highlighted the benefits of replacing the natural aggregates with spent railway track ballast and recycled concrete debris along with sand. The unsoaked CBR test results of Vertically Encased Stone Columns (VESCs) and Horizontally Reinforced Stone Columns (HRSCs) made up of recycled aggregates and sand showed improved efficiency in terms of load settlement response and strength properties. The efficiency of HESC and VESC made up of 50% spent railway ballast and 50% sand was found to be 94% and 92%, respectively, with respect to natural aggregates, whereas the least efficiency was observed for concrete debris and sand mixture (71% for HESC and 67% for VESC) among all the combinations of aggregates. It was concluded that sand can be used as a partial replacement for aggregates, and recycled aggregates are an economical and sustainable alternative to natural aggregates in building stone columns.*

Keywords - *Ground improvement, Sustainable approach, California bearing ratio test, Recycled aggregates, Horizontally Reinforced Stone Columns, Vertically Encased Stone Columns.*

1. Introduction

Stone columns are crucial in stabilizing soil and are particularly beneficial for improving soft clays, silts, and loose, silty sands. They offer a reasonably priced way to enhance the ground. The growing demand for infrastructure development in India necessitates the need for more space for infrastructure development. Land is becoming less available for construction; hence, developing soil with a high compressibility, low shearing strength, and bearing capacity is essential. The high pore water pressure developing in the soil mass drains quickly through stone columns.

The stiffness of the stone columns allows them to withstand greater shear loads, which decreases the settling and enhances the soft soil's strength and deformability. Stone column procedures are effective in enhancing the soil's bearing capacity and consolidation rate and reducing soil liquefaction. Large areas of soil mass stabilization are better suited for using stone columns. The load-settlement relationship of a single stone column under plate loading in soft clay was predicted by Hughes et al. (1975). In order to create columns, the vibro replacement approach was applied. The column's size, the clay's restriction on the gravel, and the friction angle typically utilized to cast columns affect the paramount column load.

Waste management experts face significant difficulties when it comes to disposing of construction and industrial waste, especially in more economically developed nations where there are frightening stockpiles of debris (Zukri, 2018).

The special qualities of construction debris and railway ballast can be utilized to their advantage if repurposed as a building material (TIFAC, 2000). According to a case study by Serridge (2005), crushed concrete and ballast from abandoned railway tracks were used as aggregate for stone columns in the UK. Though the ordinary stone column provides a good solution for treating soft ground, several shortcomings are associated with it (Miranda and Da Costa, 2016). Due to the lack of lateral confinement, there is a possibility of stones squeezing into the surrounding soil, thus leading to the loss of a large amount of aggregates. Stone columns may also get contaminated by the intrusion of fine particles of surrounding clay thus reducing the efficiency of the columns. All these shortcomings can be overcome by encasing the stone columns with geosynthetic material (Murugesan and Rajagopal (2009) and Alam (2024)). Manifolds can increase the performance of stone columns by encasing the stone columns with both vertical and horizontal reinforcement (Raithel et al., 2002; Alexiew et al., 2005).

Andreou et al. (2008) investigated the effects of multiple controlling parameters, such as the drainage conditions, the rate of deformation in stone columns, the confining pressure of the soil, and the grain size of the materials used in stone columns, using a series of laboratory experiments on sand and gravel. The analysis revealed that as the confining pressure increased, so did the stone column's bearing capability.

The impact of sand and aggregate used as filler material for stone columns under distributed load on consolidation has been evaluated using the unit cell approach by Ismail, 2011. Plaxis simulations on the axisymmetric model were used to interpret the rising rate of consolidation for both materials, and it was found that sand is a filler material that can hasten consolidation.

There has been a lot of research into finding sustainable materials to construct stone columns. In their experimental investigations, Sivakumar et al. (2011) took into account four recycled waste items, including freshly crushed concrete, building debris, quarry waste, and quarried basalt (for comparison), which were all tested in a variety of ways, including wet, dry, and combined with 10% and 20% clay slurry. The soil's bearing capacity improvement by including stone columns largely depends on the filler material used to construct the stone columns (Ayothiraman, 2015).

Analytical analysis conducted by Saxena and Roy (2022) showed that the greater the friction angle, φ of the stone column filler material, the greater the interlocking between particles, thus affecting the strength of columns. Moreover, granular material enclosed in geosynthetics can give more rigidity to the column material, which improves the performance of soft soil behavior in terms of strength and deformation. Tests were conducted to see if geogrids may improve the performance of these recycled waste materials. The results showed that recycled materials have much similar strength properties as compared to the quarried basalt (Chummar, 2000).

The CBR test findings on stone column models revealed an increasing order for the load capacity of virgin soil, natural aggregates, railway ballast, and concrete debris. The amount of loading necessary to induce settlement in both OSCs and GESCs showed a notable rise for recycled aggregates. Compared to virgin clay, concrete debris and railway ballast, when used as filler material in OSCs and GESCs, showed greater improvement in the load settlement behaviour of soil (Saxena et al., 2024).

For a sand column with a 38 mm diameter and 76 mm height in a triaxial device, Latha and Murthy (2007) incorporated the reinforcement horizontally and vertically and fibres in discontinuous form. They examined the stress-strain characteristics of sand columns that were encased both vertically and horizontally. Comparative research of VESCs and HRSCs was carried out numerically by Hosseinpour et al. (2014). According to their analyses, employing reinforcing layers at 0.25 D intervals over the entire column's length is the ideal configuration for HRSCs. Furthermore, horizontally oriented reinforcement layers can outperform vertical encasement when reinforced with the same amount of geosynthetics.

This is the first time in India that railway ballast and concrete debris are combined with sand to replace the natural aggregates. The primary goal of this study is to determine how well stone columns may be reinforced horizontally and vertically using different materials. The results will then be extended to a mixture of sand and various aggregates. Railway ballast, concrete debris and natural aggregates collected from specific sites were broken into standard sizes and mixed with sand in a certain proportion to make a composite column filler material.

The filler material for Geosynthetic Encased Stone Columns (GESCs) has been prepared by mixing sand and different aggregates in several proportions. The load-settlement behavior of Vertically Encased and Horizontally Reinforced Stone Columns (VESCs and HRSCs) was studied by conducting a California Bearing Ratio test on several sand and aggregates as filler material combinations.

It was found that recycled aggregates and 50% sand can replace natural aggregates, giving nearly the same efficiency as natural aggregates. Reduced costs for stone columns, better use of waste materials, and increased preservation of natural resources can be achieved by substituting some stone aggregates with sand, concrete debris, and railway ballast. As such, it has been found that alternative recycled aggregates are cost-effective and environmentally friendly.

2. Materials Used

This study uses soft clay collected from NTPC Barh Super Thermal Power Station, Barh, Bihar. Indian Standard Code 15284 (IS Code - 2003) has been followed for laboratory testing at NIT Patna for clay's various index and engineering properties. Soil was classified as Highly plastic Clay with a liquid limit of 54% and a plastic limit = 20%. The optimum moisture content of the clay was calculated as 21.7% from the Standard Proctor Test. Based on the IS Classification System, the soil is categorized as highly plastic clay based on the clay's characteristics of plasticity (CH).

The National Institute of Technology Patna campus's backyard area is where the concrete debris was gathered from demolition waste. The fragmented debris had smaller pieces ranging from 12 to 8 mm (Murugesan, 2007). From the Danapur Railway track in Patna, India, railway ballast was gathered. Stone columns were constructed using the fraction collected on an 8 mm sieve after the ballast was filtered through a 12 mm IS sieve (Dash and Bora, 2013).

The size of the natural aggregates was kept in close proximity to that of the construction waste and recycled railway ballast in order to compare their respective performances with those of the natural aggregates. In the Indian state of Bihar, aggregates were gathered from the National Institute of Technology Patna construction site. It was shattered into smaller pieces, and the fraction retained on a 10 mm sieve after passing through a 14 mm IS sieve was selected for use in the construction of stone columns.

To encase the stone columns for preparing GESCs and HESCs models, non-woven Geotextile (GSM-120) made up of polyester fibers was purchased from Siddhi Rubber Udyog, Noida, India. This textile was chosen due to its permeable fabrics that function as separation, filtration, reinforcement and drainage for the stone column-soil system. Properties of the geotextiles have been presented in Saxena et al., 2024.

The sand was collected from the backyard of NIT Patna, Bihar and a portion passing from the 4.25 mm sieve was collected and used to form the filler mix. The filler material for stone columns was prepared by evenly mixing the aggregates with sand in specified proportions, as shown in Table 1.

Table 1. Ratio of aggregates and sand used for filler material in VESCs and HRSCs

Aggregate	Proportion
Sand	100%
Concrete Debris (CD)	100%
Railway Ballast (RB)	100%
Natural Aggregates (NA)	100%
CD and Sand	50% and 50%
RB and Sand	50% and 50%
NA and Sand	50% and 50%

3. Model Setup and Testing

3.1. Modeling Considerations of Vertically Encased Stone Columns (VESC)

A sufficient quantity of clay was taken from the Barh, Bihar, NTPC Barh Super Thermal Power Station. Water was added to the soil after the OMC was determined, ensuring that every test was carried out with the same volume of water. The unit cell model of a geosynthetic encased stone column was prepared inside CBR mould using geotextile with properties as shown in Table 2.

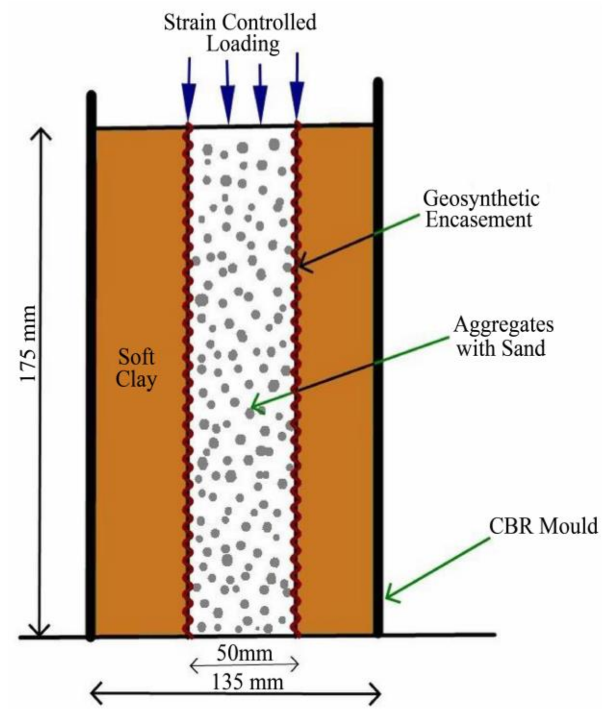

Fig. 1 Schematic of CBR test on GESC

The detailed procedure adopted for the test set-up was described by Saxena et al., 2024. Aggregates sand mixture (Table 3) was filled inside the geosynthetic encasement inside the casing pipe in 3 layers.

Tamping was done 25 times on each layer with a constant force. The casing was carefully removed to finish creating the encased stone column inside the CBR mold, as illustrated in Figure 1.

3.2. Modeling Considerations of Horizontally Reinforced Stone Columns (HRSCs)

Clay was collected from NTPC, and the barh site was prepared by adding water equal to OMC. In order to prepare horizontal geosynthetic encasements, the geotextile was cut into circles with a diameter of 135 mm. Clay was filled in the CBR mould in 5 layers with proper tamping. After every 35 mm thickness of clay, one circular piece of geotextile was placed over the clay layer.

Again, the clay was filled over the geotextile up to 35 mm, and a second piece of geotextile was placed over it. This process was repeated 5 times to completely fill the mould. Figure 2 illustrates the schematic of HRSC in the CBR mould. Four horizontal layers of geogrids were used in totality for the entire span of 175 mm depth.

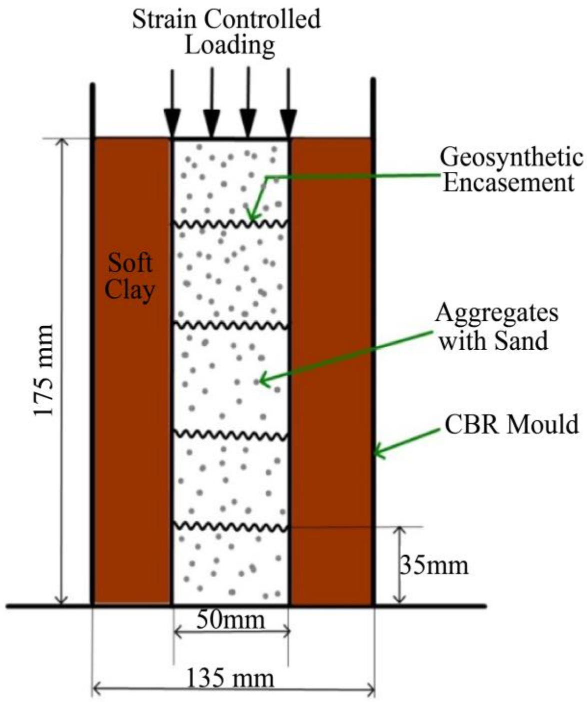

Fig. 2 Schematic of CBR test on VESC

3.3. Test Procedure

Once the penetration piston was seated in the specimen's centre, the mould assembly was mounted on the testing apparatus and exposed to a 1.25 mm/min penetration rate. In order to test the performance of various aggregates used as the material for stone columns, a loading piston placed the load directly over the columns (Murugesan, 2009). Using proving rings, the loads associated with various settlements were measured.

In order to compare the performance of soil with that of different kinds of stone columns, a CBR test was first conducted on virgin clay without any stone columns. Next, the CBR tests were run on both VESCs and HESCs for every combination of sand and aggregates.

4. Results and Discussions

The load-settlement curve of the CBR test demonstrates that as the load increases, the settlement also increases. Stones and sand from every CBR test exhibit the same load-settlement behavior. The compacted density for all tests on aggregates was maintained to be approximately the same by evenly tamping the aggregate sand mixture.

The geosynthetic reinforcement plays a crucial role in enhancing the load capacity of stone columns comprising aggregates with coarse sand by giving enhanced lateral support in the case of VESCs (Figure 4). On the other hand, the ultimate carrying capacity of stone columns with horizontal reinforcement is exceptionally high. This is because the column materials are restricted between the horizontal reinforcement layers, adding more confinement, which is caused by the mobilization of shear stress between the reinforcing sheets and granular materials, which reduces the lateral bulging (Figure 5).

4.1. Load- Settlement Behavior of Virgin Clay

A trial experiment on virgin clay was conducted to compare the behavior of crushed stone aggregates and sand with that of virgin clay without any stone column. Figure 3 depicts the load-settlement behavior of virgin clay as determined by the CBR test. The CBR of NTPC clay was found to be 27%, and its efficiency towards load-settlement behavior was found to be only 55% concerning soil reinforced with a stone column made up of natural aggregates.

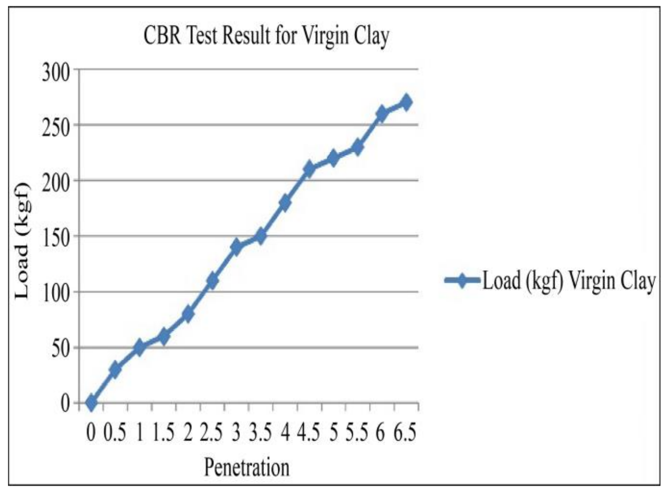

Fig. 3 Load-settlement behavior of virgin clay

4.2. Load- Settlement Response of VESCs

Individual CBR tests were performed for each combination of filler aggregates (Table 1). Figure 4 displays the typical load-displacement response derived from model testing of various sand and stone aggregate mixes. A consistent form of load-settlement curve was seen across all of the trials (as shown in Figure 4), demonstrating the reproducibility of the experimental approach used in this study.

As observed in Table 2, the stone column constructed entirely of sand has a lower CBR value and thus lower efficiency concerning natural aggregates (almost half) or any other recycled stone aggregate alone. The CBR% of VESC made from railway ballast is 54%, which is 2 times the CBR% of VESCs that are composed only of sand (27%).

From the results of the CBR test, it can also be inferred that the efficiency of stone columns made from 100% concrete debris is almost the same as the efficiency of GESCs made of 50% NA + 50% sand. The CBR value for each combination of filler material was calculated, and the combination of RB (50%) and sand (50%) was found to show a similar load-settlement trajectory as 100% Natural Aggregates (NA).

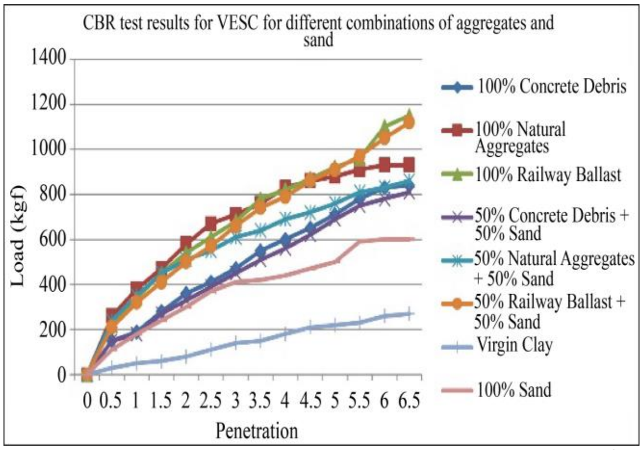

Fig. 4 Load-penetration response determined by model testing of different combinations of aggregates and sand for VESCs

The efficiency of different combinations of filler material is calculated in terms of NA (Table 2). The combination of 50% RB and 50% Sand has shown an appreciable load-carrying capacity of 92% with respect to the VESC made purely of NA. Moreover, upon replacing 50% natural aggregates with sand, the load capacity decreased by only 20%, showing the great potential of sand as a material for stone columns when combined with other hard and inert aggregates. On the other hand, the mixture of 50% CD and 50% sand has shown a remarkable decrease in load-settlement response due to the low-strength properties of concrete debris. Moreover, when CD was used alone as filler material, it gave an efficiency of 76% with respect to VESC made purely of NA.

Table 2. CBR results for VESCs with different combinations of filler material

Filler Material of VESC	CBR %	Efficiency %
100 % Sand	27	55
100 % Concrete Debris (CD)	38	76
100% Railway Ballast (RB)	54	110
100% Natural Aggregates (NA)	49	100
50% CD + 50% Sand	33	67
50% RB + 50% Sand	45	92
50% NA + 50% Sand	39	80
Clay without stone column	11	22

4.3. Load- Settlement Response of HRSCs

Like VESCs, individual CBR tests on HRSCs were performed for each combination of filler aggregates. A consistent form of load-settlement curve was seen across all of the trials (as shown in Figure 5), demonstrating the reproducibility of the experimental approach used for HESCs. The CBR value for each combination of filler material was calculated, and the combination of RB (50%) and sand (50%) gave an appreciable CBR value of 46%. Moreover, NA(50%) and sand (50%) were also found to show a CBR value of 45% (Table 3). From the results of the CBR test, it can also be inferred that the efficiency of HRSCs made from 100% CD has been reduced by around 27% compared to HRSCs made from natural aggregates. Furthermore, after replacing 50% of concrete debris with sand, the efficiency of the stone column was further reduced to 71%, with respect to the stone column made from 100% NA.

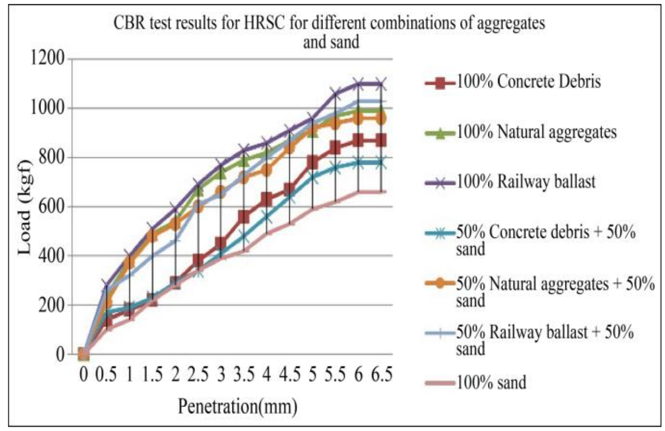

Fig. 5 Load-penetration response determined by model testing of different combinations of aggregates and sand for HESCs

Table 3. CBR results for HESCs with different combinations of filler material

Filler Material of VESC	CBR %	Efficiency %
100 % Sand	29	59
100 % Concrete Debris (CD)	38	77
100% Railway Ballast (RB)	50	102
100% Natural Aggregates (NA)	49	100
50% CD + 50% Sand	35	71
50% RB + 50% Sand	46	94
50% NA + 50% Sand	45	92

4.4. Load- Settlement Response of HRSC and VESC Made of Sand Alone

The sand particles are much smaller than the recycled aggregates; they could behave differently after loading over the CBR apparatus. Separate tests were carried out on VESC and HESC models composed of sand alone to assess the impact of loading on stone columns composed of sand, as illustrated in Figures 6 and 7. The load-penetration curve of a stone column comprising sand alone suggests that while the loading behavior is generally the same, the column's failure load and loading trajectories are different. As expected, the VESCs and HRSCs constructed entirely of sand had lower CBR values (27% and 29%, respectively). Like VESC, the HRSC, composed purely of sand, had lower efficiency in relation to natural aggregates (almost half). This is mostly due to the fact that sand is insufficient on its own to fulfil the essential roles of reinforcement and enhance the soft soil's strength and deformation characteristics. It is obvious from this that sand alone will not give appreciable results in increasing the load capacity of the soil reinforced with VESC and HRSC.

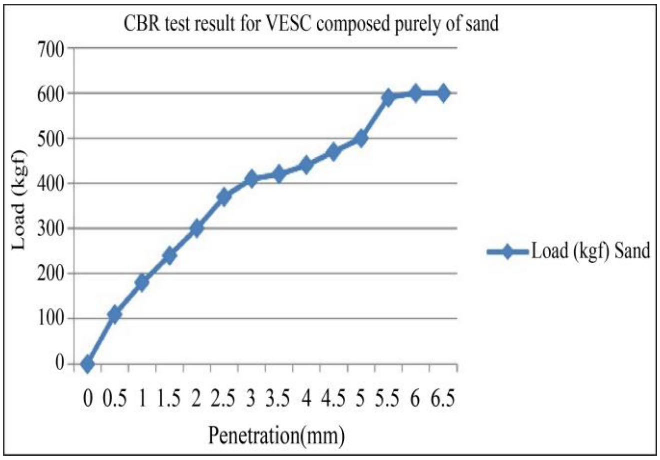

Fig. 6 Load- penetration curve for VESC composed of sand

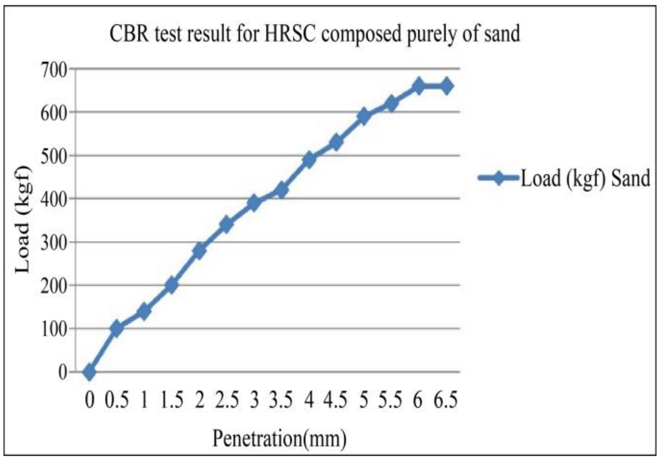

Fig. 7 Load- penetration curve for HRSC composed of sand

5. Conclusion

Model experiments were conducted on stone columns consisting of various material combinations. Sand passing through a 4.75 mm sieve was utilized, and a total of thirty tests were run (two trials for each combination) for VESCs and HRSCs to ensure that the materials could apply to field problems with the various recycled aggregates and sand mixtures. The load-settlement curves for different combinations of aggregates and sand were discovered to be comparable. The difference in load-carrying capacity between clay and crushed aggregates for the same settlement is fairly high, approximately 2.5 times for VESCs and approximately 3 times for HRSCs. This adds credence to the finding that VESC and HRSC, made up of a mixture of sand and aggregates, can be used as filler material in stone columns. Following are some of the major conclusions of the study:

- In the case of VESCs, a mix proportion of 50% RB + 50% Sand was found to have nearly the same efficiency in load-penetration response as that of 100% NA.
- Sand alone is not providing sufficient efficiency in terms of load-penetration response. But when mixed with recycled aggregates and natural aggregates in half quantity of the total volume, the load capacity of the resulting filler material increases many times both for HRSCs and VESCs.
- The load-penetration curve of the stone column comprising sand alone suggests that while the loading behavior is generally the same, the columns' failure load and loading trajectories for various combinations are different.
- The combination of 50% CD + 50% Sand gives a low efficiency, 67% in VESC and 71% in HRSC, as compared to 100% NA, but when CD is used alone as stone column material, its efficiency is found to be 76% and 77% respectively in VESC and HRSC.
- Apart from this, the quantity of natural aggregates can be reduced by replacing it with 50% RB + 50% sand for both VESC and HRSC to increase efficiency.
- It was determined that stone columns maintained similar load-bearing capacity with partial replacement of aggregates—up to around 50%— with sand. A decrease in the quantity of stone aggregate needed will lower the price of stone columns, improve waste material utilization, and safeguard natural resources.

Similar results were obtained by Ismail et al. (2011) and Ghazavi et al. (2018) regarding the improved load-bearing capacity of VESCs and HRSCs in their research. The results clearly show that combining recycled stone aggregates and sand would result in a substantially higher load-carrying capability for stone columns due to their increased interlocking and similar engineering properties.

The results of this study are found to align with the findings of Ayothiraman (2015). Lowering the number of stone aggregates by replacing a portion with sand, concrete debris, and railway ballast will result in lower stone column costs, improved waste material utilization, and greater preservation of natural resources. Consequently, it has been demonstrated that using other recycled aggregates is an economical and sustainable method. Nevertheless, the aforementioned findings are derived from laboratory model experiments, so the conclusions and suggestions must be confirmed based on extensive testing carried out at the site location to create design guidelines prior to putting recycled aggregates and sand into practice in the field.

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