An experimental study of the behaviour of granular columns reinforced with post-consumer plastic bottles

Une étude expérimentale du comportement de colonnes granulaires renforcées de bouteilles plastiques post-consommation

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ABSTRACT: The conventional granular column technology has regularly demonstrated its effectiveness and versatility. Due to the high challenges surrounding ground conditions for construction, methods of improving the ground remains of high interest. As such, one of the emerging concepts is the reinforcing of granular columns, both externally and internally. Several researchers have undertaken studies in this area of research and yielded positive outcomes. However, it appears that the use of waste materials to reinforce the columns is rather unpopular. Due to the problems surrounding plastic waste disposal, this study proposed and investigated the effect of reinforcing granular columns with flakes generated from waste PET bottles. A series of laboratory tests were performed on singular columns reinforced with randomly incorporated PET flakes. The load-settlement relationships obtained from the results demonstrated that the load carrying capacity of the column may increase while on certain situations, the maximum lateral deformation of the column may beneficially be reduced. Flakes concentration of 0.5 % and 2.5 % appeared to produce the highest improvement in load carrying capacity and lateral deformation reduction, respectively.

RÉSUMÉ: La technologie conventionnelle des colonnes granulaires a régulièrement démontré son efficacité et sa polyvalence. En raison des défis importants entourant les conditions du sol pour la construction, les méthodes d'amélioration du sol restent d'un grand intérêt. En tant que tel, l'un des concepts émergents est le renforcement des colonnes granulaires, tant à l'extérieur qu'à l'intérieur. Plusieurs chercheurs ont entrepris des études dans ce domaine de recherche et ont donné des résultats positifs. Cependant, il apparaît que l'utilisation de déchets pour renforcer les colonnes est plutôt impopulaire. En raison des problèmes liés à l'élimination des déchets plastiques, cette étude a proposé et étudié l'effet du renforcement des colonnes granulaires avec des flocons générés à partir des déchets de bouteilles en PET. Une série d'essais en laboratoire a été réalisée sur des colonnes singulières renforcées de paillettes de PET incorporées de manière aléatoire. Les relations charge-tassement obtenues à partir des résultats ont démontré que la capacité de charge de la colonne peut augmenter tandis que dans certaines situations, la déformation latérale maximale de la colonne peut être avantageusement réduite. Une concentration de flocons de 0,5 % et 2,5 % a semblé produire la plus grande amélioration de la capacité de charge et de la réduction de la déformation latérale, respectivement.

KEYWORDS: Ground improvement, soil reinforcement, granular columns, PET bottle waste.

1 INTRODUCTION

Ground improvement has emerged as one of the most economical and rather quick approach to addressing undesired ground conditions for construction projects. In South Africa, it has been reported that approximately 50 % of the soil coverage is problematic for construction purposes (AGIS 2011). Hence, there is a need to explore new methods to address both the local and global ground challenges.

Out of the many approaches, the granular column technology is one which is popular for its versatility and cost effectiveness. Generally, the inclusion of columns has demonstrated significant improvement in bearing capacity and settlement reduction. Although the technique has been used across the globe for a few decades, it remains appealing to engineers today. This has encouraged additional advances which have demonstrated that the loading and settlement performance of granular columns can be further enhanced by reinforcing the column internally or externally (Sobhee-Beetul 2019). Besides, reinforcing tends to reduce lateral deformation which is necessary to avoid bulging failure. This study investigated the effect of internally reinforcing granular columns with PET flakes which were generated from used plastic bottles. The aim was to create a technology which will contribute towards solid waste minimisation to landfills while at the same time re-using resources with the potential reduction of the carbon footprint associated with PET bottles. PETCO (a regulating body for PET recycling in South Africa) claimed a recycling rate of about 65% in 2017 (Petco 2018). Plastics SA, a representative of all sectors of the South African Plastics Industry, has set itself a target of "Zero plastic to landfills by 2030" (Plastics SA 2019). Several of the polymer associations locally, including PETCO, have committed to work towards this goal such that the objectives were aligned with the Government's National Development Plan. A key area which was identified as important was the research and development into different technologies and markets. This study was, therefore, considered valuable to both geotechnical engineering and plastic waste management.

2 LABORATORY INVESTIGATION

For this study, a total of 10 experiments were undertaken on 100 mm diameter singular columns which were each 400 mm long. Each test was conducted in a 300 mm diameter bespoke steel cylindrical tank of height 450 mm within which the silt beds were formed. Repeatability tests were performed to ensure that the testing procedure and results obtained were repeatable. The repeatability relative standard deviation was less than 5 % for all the results, which was considered as the acceptable upper limit for this study. More information regarding repeatability may be obtained from Sobhee-Beetul (2019). Two types of variables were used in this namely: the moisture content of the silt (Optimum Moisture Content and Liquid Limit) and the PET flakes content (0, 0.5, 1.0 and 2.5 %) which was measured as a percentage of the mass of the sand. Two significantly different degree of wetness were preferred for the base silt to understand how the columns behave under each condition. In terms of the flakes content selected, the percentages were based on an analysis of existing literature (Benson & Khire 1993, Consoli et al. 2002, Dutta & Sarda 2007, Choudhary et al. 2010, Sivakumar et al. 2010, Sobhee-Beetul & Kalumba 2011, Laskar & Pal 2013).

2.1 *Properties of materials*

Intensive research has been conducted with regards to reinforcing soils with plastic wastes. The outcome has often confirmed plastic as a potential soil reinforcement material, hence the choice of this material for this investigation (Benson & Khire 1993, Dutta & Sarda 2007, Sivakumar et al. 2010, Sobhee-Beetul 2012). In the past, several studies have been conducted on granular columns; the type of column material researched varied from finer particles to much coarser ones, amongst which sand and crushed aggregates are the most common ones (Ambily & Gandhi 2007, Sivakumar et al. 2007, Sobhee-Beetul 2012). In the current study, sand was used as the primary material for the column since it is readily available locally. Furthermore, the smaller particles of the sand compared to that of stones, allowed for soil reinforcement within each column without damaging the PET flakes under compressive or shearing stresses. The particles of the sand, which was referred to as the Cape Flats sand, varied between 0.075 and 1.18 mm in size. A dry sieve analysis on the material revealed that 98.9 % of the sand particles were smaller than 1.18 mm. The sand had a specific gravity of 2.70, and a coefficient of uniformity and a coefficient of curvature of 2.83 and 0.98, correspondingly. The respective Optimum Moisture Content (OMC) and the Maximum Dry Density of the sand was 12.5 % and 1795 kg/m^3.

To replicate a ground of poor loading condition, a wet silt was filled in the cylindrical testing tank. The base silts were prepared by passing the soil material through a 4.25 mm sieve whereby it was found that 79.4 % of the particles were less than 0.075 mm. Laboratory tests performed on the sieved silt yielded the following properties: specific gravity of 2.71, Liquid Limit (LL) of 37 %, plastic limit of 30.6 %, Optimum Moisture Content of 17.7 % and Maximum Dry Density of 1700 kg/m^3.

In terms of the reinforcement, locally sourced PET flakes were used which were obtained as a product during the initial stages of the recycling process of used PET plastic bottles; the flakes are generated when the PET bottles undergo the shredding process. The flakes were irregular in shape with a smooth surface. Their sizes ranged between 2.36 and 9.5 mm in length.

2.2 *Sample preparation*

Predetermined masses of dry silts were mixed with water in a mechanical mixer. The required mass of moist silt prepared for a single test was then stored in airtight plastic containers to allow for even distribution of water within the soil mass. After 24 hours, the testing tank was securely fitted on its trolley assembly and the mixture was transferred in 8 layers in the testing tank to a height of 400 mm. For silts at OMC, each layer was compacted by a 2.5 kg hammer which was dropped 15 times through a height of 180 mm. The applied energy was predetermined such that a dense layer was formed without causing crushing of soil particles; the resulting compaction energy of 66 J was kept constant for each layer to attain an average bulk density of 1415 kg/m^3 for the prepared silt bed. For silts at LL, each layer was manually pressed down to expel as much air pockets as possible to obtain the densest possible state; compaction was not possible due to the high degree of saturation in the silt. The bulk density of the silt at LL was 1556 kg/m^3.

Once the silt bed was formed, a 100 mm diameter cylindrical metal tube was lightly greased and pushed through the centre of the bed until the base of the tank was reached. The silt within the tube was augered out and the inner surface was wiped to avoid smudging during the formation of the column. To form the latter, a mix of oven dried sand and PET flakes was first prepared. The respective mass of sand was predetermined to ensure that a layer of 50 mm was attained post compaction; this process involved several trials including mixes of the sand and flakes. Flakes required was a percentage of the mass of the sand being used for each layer. Once measured, both the sand and the flakes were randomly mixed in a bowl. A set mass of the mix was then poured into the tube to form the first layer of the column. The tube was retracted by 35 mm to allow for proper interaction of the column material with the surrounding silt. The layer was then compacted using a 2.3 kg hammer which was dropped 12 times through a height of 180 mm such that each layer was subjected to a compaction energy of 49 J. This procedure was repeated 8 times to obtain a 400 mm long column which was levelled with the silt bed.

The prepared sample was then shifted from the trolley assembly to the loading machine where it was subjected to a displacement-controlled (speed of 1.2 mm/min) compressive load, through a 25 mm thick loading plate of diameter twice that of the column. The testing speed was based on previous studies (Sobhee-Beetul 2012, Murugesan and Rajagopal 2008). The test was terminated once a settlement of 50 mm was reached. This maximum allowable settlement was based on the value recommended for normal structures in the Eurocode 7 (BS EN 1997-1:2004). Although the settlement was rather large for the scale at which the test was undertaken, it was nevertheless considered necessary to understand the performance of the reinforced columns under excessive loading. The loading speed was selected to allow for undrained testing conditions. Load settlement characteristics were electronically captured and later used in the analysis of experimental data.

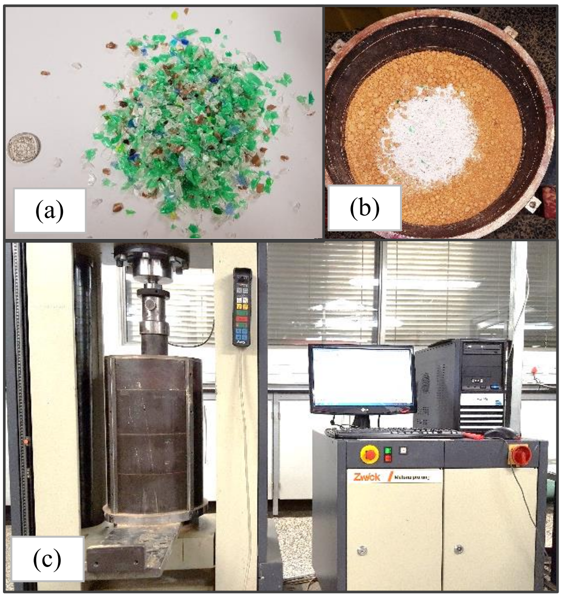


Figure 1. (a) PET Flakes ready for mixing with sand, (b) Reinforced granular column installed and ready for testing, and (c) Test in progress.

Upon completion of an experiment, the tank was carefully removed from the machine and the columnar material was vacuumed out to obtain the empty column space. A wet mixture of plaster of Paris and sand was then gently poured into the opening, and it was allowed to set. After 2 hours, the surrounding silt was manually removed, and the physical model of the column deformation was obtained. Measurements for each test column were taken at several intervals along its length. The same procedure was followed for all tests, including the ones on silts at LL, such that the effect of the different variables was studied. Additional details of the experimental approach may be obtained from Sobhee-Beetul (2019). The results from the tests are presented in section 3.

2.3 *Testing programme and overall results*

The testing programme in this investigation is provided in Table 1 and a summary of the maximum vertical applied stress, the maximum bulging, and the length span over which maximum bulging occurred have been given; these values correspond to a maximum settlement of 50 mm which was attained at the completion of the test.

The symbols used in the test codes are described as follows: M1 for Optimum Moisture Content (OMC), M2 for Liquid Limit (LL), S for sand, R for random arrangement, P for PET flakes. The given percentage in each code represents the PET flakes content utilised in the respective test.

Table 1. Testing programme and summary of laboratory results at a maximum settlement of 50 mm.

Test code	Vertical stress (kPa)	Bulging (mm)	Length of span (mm)
M1	203	-	-
M1-S	413	128	40
M1-S-RP0.5%	425	135	15
M1-S-RP1.0%	382	125	15
M1-S-RP2.5%	397	137	10
M2	30	-	-
M2-S	52	150	50
M2-S-RP0.5%	72	164	10
M2-S-RP1.0%	69	152	20
M2-S-RP2.5%	61	144	15

3 RESULTS

In this section, the results for the load-settlement relationships and the column deformations are presented. In addition to the results obtained for tests with reinforced granular columns, all figures include results for tests conducted on an unimproved silt bed and on a bed which was improved using an ordinary granular column, which were undertaken under similar testing conditions. Results for tests performed on silts at OMC and LL have been presented independently.

3.1 *Stress-settlement behaviour of treated ground*

Figure 2 shows the stress-settlement relationships obtained in the tests undertaken on silts at both OMC and LL. The general trend observed in the shape of the graphs for silts, at both moisture contents, indicate a gradual increase in settlement when subjected to a vertical stress. All curves follow similar shapes which confirm the identical behaviour of the columns irrespective of the arrangement of the PET flakes. However, at a maximum displacement of 50 mm, each test displays distinct load carrying capacities. Despite the differences in the loading response of the improved silt bed, the inclusion of a granular column (ordinary or reinforced) has repeatedly confirmed an improvement in strength of the moist silt.

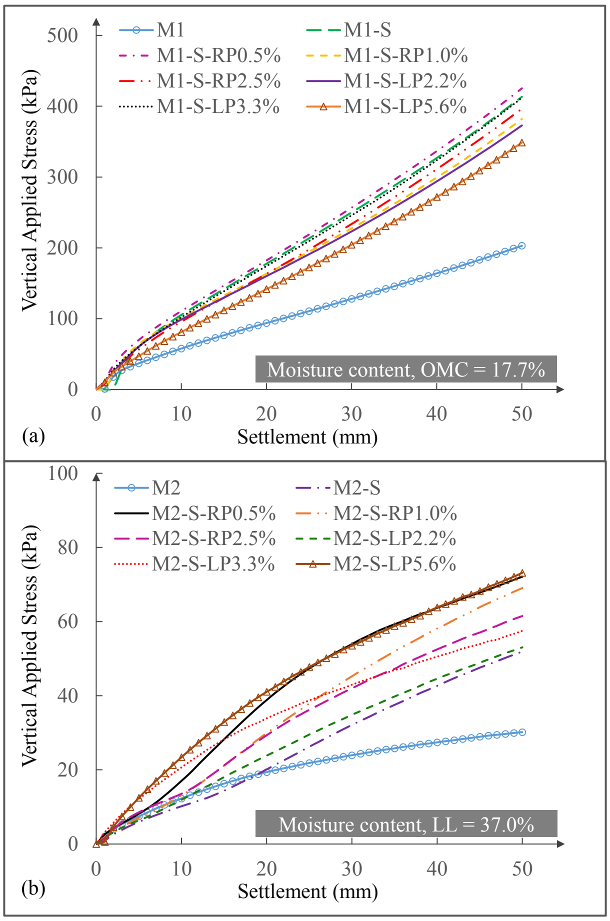


Figure 2. Stress-settlement relationships for tests on silts at (a) OMC, and (b) LL.

From the stress-settlement graphs, the maximum vertical applied stress at a settlement of 50 mm can be used to calculate the percentage improvement (with reference to the unimproved silt bed) achieved when treating a moist silt with both ordinary and reinforced granular columns. Generally, it was noted that a percentage improvement of at least 73% was obtained with the inclusion of a column.

At OMC, the highest improvement of 109% was recorded in a column which was reinforced by 0.5% of flakes. This represents an additional increase of only 5% when compared to the enhancement of 103% obtained for the ordinary granular column. In fact, 109% was the highest improvement noted in the OMC test series. The stress performance of all the remaining tests were lower than that of the ordinary column; however, at LL the observations differed drastically. Ordinary granular columns displayed the lowest loading strength while sand columns reinforced with 0.5 % of flakes layers exhibited the highest performance, represented as 140%. The enhanced may possibly be explained in terms of the strong interlocking of the silt particles around the surfaces of the flakes, thus forming a stronger column material.

The average lower performance noted at OMC can possibly be explained in terms of the anticipated high stiffness of the silt at this degree of wetness. Since a stiff silt is relatively strong, the inclusion of a granular column does not offer tremendous improvement. On the contrary, the addition of the flakes reduced the strength (compared to that of ordinary granular columns) in most cases since the interaction between the sand/plastic and the surrounding silt is poor. The high confinement pressures exerted by the stiff clay on the composite column explains this behaviour. Nevertheless, in the softer silt, this reduced intensity did not affect the performance of the column as much since the silt-column interaction was much better as a result of the lower confining pressures from the surrounding silt. Hence, as the column bulged, the interaction between the flakes and sand possibly produced higher shear stresses which was further raised by the surface of the column embedding into the silt.

3.2 *Bulging behaviour of the columns*

The generation of the physical model of the column allowed for accurately establishing the deformation of each column. It was, thus, possible to identify the diameter of the maximum bulge and the position at which it was formed along the column. Figures 3 and 4 provides a graphical as well as a pictorial representation of the deformation pattern for the columns in the respective tests. The graphical plot assumes a symmetrical deformation for ease of plotting. This assumption does not affect the numerical representation of the maximum lateral deformation which occurs at any one point since the circumference remains the same. More information regarding the approach for plotting the column deformation may be obtained from Sobhee-Beetul (2019).

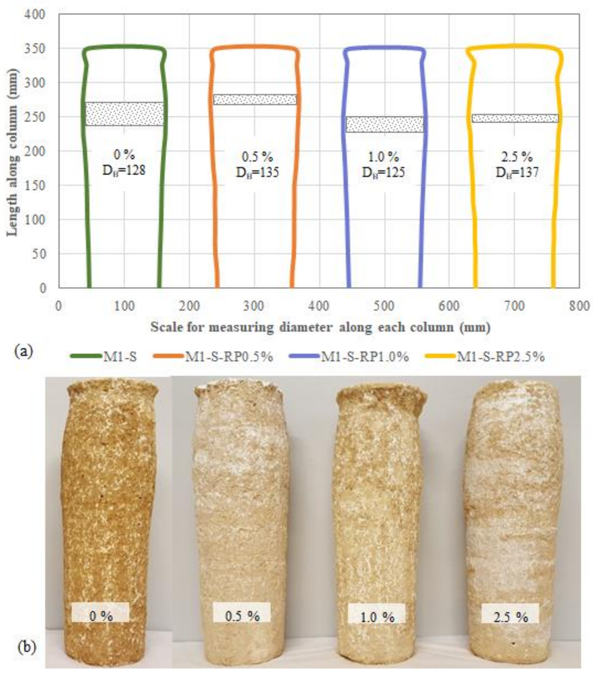


Figure 3. Column deformation for tests on silts at OMC, (a) Graphical plot and (b) Pictorial representation.

The information obtained from figures 3 and 4 have been used to determine the largest bulge and the length of the span over which it occurs. The summary of this information is given in Table 1. In terms of the depth corresponding to lateral bulging, most bulging occurred between the top third to two-thirds of the column length at OMC and within the top third of the column at LL. Similar observations have been made by McKelvey et al. (2004) and Sobhee-Beetul (2012). The lower depth at which maximum bulging occurs can be explained by the low stiffness of the clay which, therefore, provides weaker lateral confinement stresses. Thus, bulging occurs at a much higher length along the column than in the stiffer clay. Owing to these low confining stresses, the largest deformations evidently occurred in tests conducted on silts at LL. It was also observed that the length span over which the maximum bulge occurred decreased in all tests where reinforced granular columns were used. Therefore, it can be said that reinforcing of granular columns with PET flakes reduced the length span of maximum bulging, irrespective of the plastic concentration. To understand the effect of the flakes concentration on maximum bulging, graphs were plotted based on the information given in figures 3 and 4. The relationships are presented in Figure 5.

Figure 4. Column deformation for tests on silts at LL, (a) Graphical plot and (b) Pictorial representation.

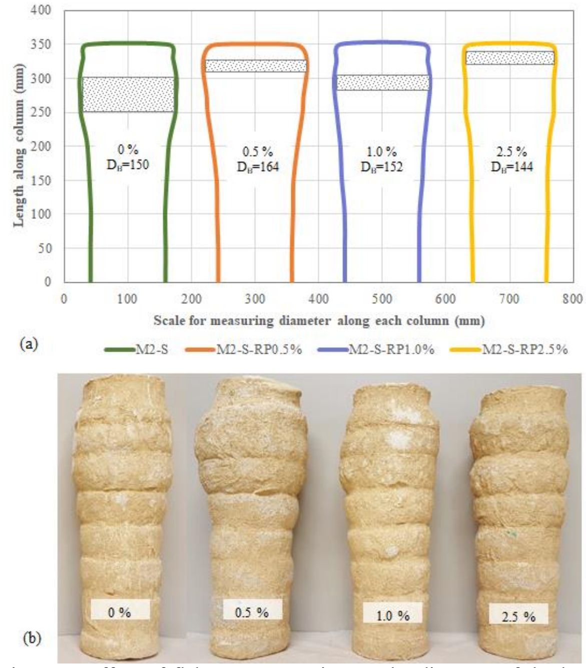
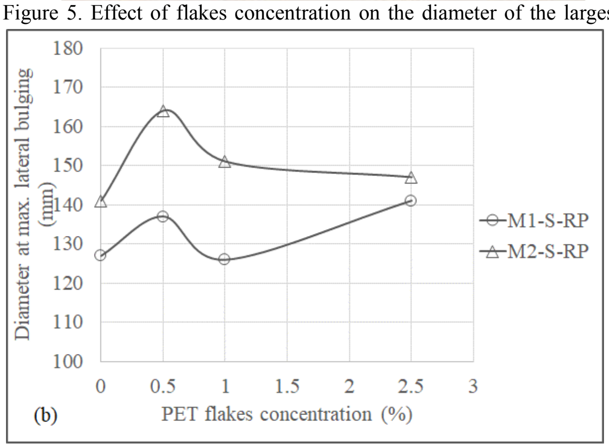


Figure 5. Effect of flakes concentration on the diameter of the largest



bulge

Figure 5 shows similar trends for tests conducted on silts at both moisture contents, except at a concentration of 2.5 %. At this concentration, the largest bulge seems to continue decreasing for tests on silts at LL. However, an opposite observation was made for the test at OMC whereby the bulge drastically increased. More tests are recommended on larger concentrations to identify whether there is any additional increase in bulging when the flakes content is augmented. More information regarding the bulging behaviour may be obtained from Sobhee-Beetul (2019).

4 CONCLUSIONS

This study investigated the effect on loading strength and column deformation when granular columns, made from sand, were reinforced with PET bottle waste (in the form of PET plastic flakes). A series of laboratory tests were undertaken to obtain the load-settlement and column deformation characteristics when the following were varied: the moisture content of the base silt and the concentration of the PET flakes.

The results showed that these flakes can potentially be used for reinforcing granular columns. When a sand-plastic composite column is installed in a moist silt, the percentage improvement is higher in a silt prepared at Liquid Limit as opposed to one at Optimum Moisture Content.

It is further observed that the lowest plastic concentration of 0.5 % provides the highest improvement in load carrying capacity, irrespective of the moisture content of the base material. In fact, in tests on silts at OMC, the loading strength reduce to a value lower than that for an ordinary granular column. The largest enhancement was recorded in the test where the silt was at LL and the column was reinforced with a flakes concentration of 0.5 %.

In terms of the bulging behaviour, the inclusion of PET flakes appeared to increase bulging except in the test with silt at LL and a flakes content of 2.5 %. Nevertheless, the length span over which maximum bulging occurred was remarkably reduced.

Although the results obtained from this study are promising and support the concept of reinforcing granular columns with PET waste, the technology may not be implemented with the present information due to several limitations. Therefore, it is recommended for further studies to be undertaken to study important aspects such as: the effect of the concentration of the flakes on the shear strength of the reinforced sand, the scale effect when field experiments are undertaken, the drainage effect when reinforcing and the practicality of installing the reinforced columns on a large scale.

5 ACKNOWLEDGEMENTS

The authors would like to extend their thanks to the Geotechnical Engineering Group at the University of Cape town for funding this research. The efforts of the following individuals in the civil engineering department at the same university is also appreciated for assisting in the experimental works undertaken: the laboratory manager, the workshop manager and the laboratory technicians. A word of thanks is also extended to the respective companies, Kaytech Engineered Fabrics for supplying the PET flakes and Corobrik for supplying the silt.

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