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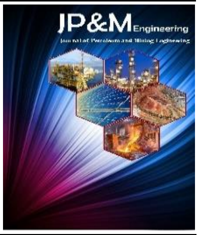


# Chemical stabilization of sands with SS21. Case of study: fine sands from the Argentinean Delta

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## Abstract

The stabilization of coarse grained soils is a recurring problem in geotechnical engineering around the world due to the condition of these soils while using them for build-ups, highways, infrastructure, and other common applications in engineering practice. Coarse soils, and particularly sands, are materials composed by particles, where gravitational forces predominate over attractive ones. This particular behaviour, makes it necessary to apply a differential approach in comparison with fine grained soils where the problem is focused on the attractive forces. Based on years of experience in Chemical and Geotechnical engineering, HyGT Chemical SRL (HyGT) and Weg Consultora de Ingenieria SA (WEG) have jointly developed the product HyGT SS21® (SS21), a polymer capable of generating interesting engineering properties in coarse grained soils, particularly developed for sands, the starting point of the development.

After an outstanding performance in laboratory and in field, SS21 has been considered for a formal scientific publication, to show the laboratory test results and potential applications of this product, being in roads, infrastructure, oil and mining, places where it is common to have roads, embankments and slopes on granular soils. The importance of addressing this solution for a real application case, in the case of sands extracted from the Argentinean Delta, will be demonstrated throughout the document. Results of routine tests in road works will be presented, possible to be replicated in all types of facilities, and draw conclusions in reference to them.

## Introduction

During the progress of geotechnical engineering in roads, traditionally, the stabilizations were carried out with Lime and/or Cement, as agents frequently used in the construction industry for various uses. Their availability and low cost made them suitable for use in these processes.

The chemical stabilization of soils is a process that involves the integration of an agent into the soil, generally in low to medium amounts, which allows the modification of its engineering properties through a chemical process.

As technology progressed, new technologies emerged and allowed the development of more complex materials, of polymeric origin, which allow reducing the use of traditional materials, which are in high demand in other areas of the industry. In turn, these materials have made it possible to improve both handling, storage, speed and processes, which are developed during soil stabilization.

This is the case of SS21, a polymer-based product, developed in order to provide a mono-product specific solution for the coarse grained soil stabilization, contemplating the original flaws in these solutions across the history of soil stabilization and engineering practice.

Particularly, granular soils, of a predominant sandy and/or gravel type behaviour, are a particularly serious geotechnical issue on the surface or near surface area: Their lack of confinement does not allow their frictional capacities to fully develop, resulting in poor performance under certain circumstances. The use on roads and embankments is a good example. In addition to this, the effects of tensile and shear forces on the surface, due to the passage of vehicles, generate detachment of particles, formation of "saws" and general erosion/wear of mechanical origin. To this must be added, hydraulic and wind erosion, a product of inclement weather. The result: poorly performing roads, rutting, erosion, dust kicking and putting roads out of service, requiring intervention in the short term.

With the chemical stabilization of these soils with SS21, it has been possible to add a property of adhesion between the particles, which has considerably improved the properties of granular soils, even in unconfined conditions, making it possible to perform tests and even moulding of specimens without further complications. It has been possible to perform bending tests on sand+SS21 specimens, that is an interesting condition for a soil with no cohesion and self-standing properties in unconfined condition.

The selection of the case study, is particularly related to the frictional properties of the soils, with the objective of isolating the particular properties of a sand, without relevant content of fines, in order to fully estimate the potential of SS21, on the worst condition: a soil that would not allow specimens to be moulded or have resistance in an unconfined condition.

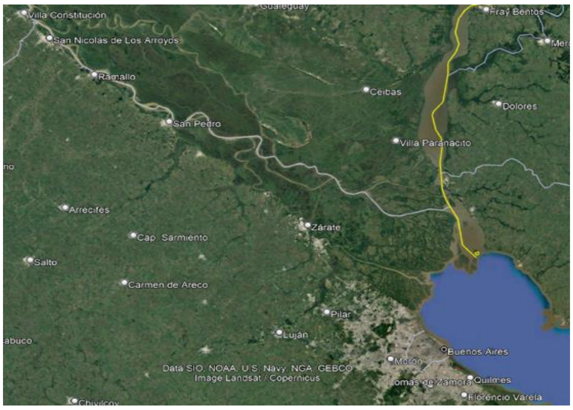


**Figure 1** Outfall of the Paraná Delta, in conjunction with the Río de la Plata. Image obtained from Google Earth

It is a uniform sample of fine sand from the Paraná River Delta, the main source of sand in Argentina, usually used in construction, and present to a large extent on the shores of the Paraná River and its tributaries, which flow into the Río de la Plata. General basic characterizations were carried out on this sand and later routine road type tests in paving works, and other tests, with the aim of obtaining a detailed characterization of the behaviour.

It is shown that the application of SS21 as a chemical stabilizer has a great impact on the performance of roads, embankments, slopes and similar geotechnical elements, for granular soils, in infrastructure, oil and mining works.

## Materials used

### Sand

To carry out the tests, a sample of uniform fine sand was obtained, coming from sand establishments located in the Northwest area of the province of Buenos Aires. The origin of the sand is the surrounding area of the city of Ibicuy.

Petrographically, it is a sand with a high quartz content, and predominantly around 90 to 95%, with a solid particle density of 2650 kg/m3. It is a non-reactive type of sand, with no particular characteristics to report, found in abundance in the Paraná Delta.

Sieve analysis tests were carried out on the sand sample in order to determine the distribution of grains in the curve, and obtain the reference parameters for both geotechnical interest and interest as an aggregate. In this way, the through-passes of each ASTM E11(2) sieve of interest for the case were determined by dry granulometry, the coefficient of uniformity (Cu), the coefficient of curvature (Cc), the modulus of fineness (MF) and the contribution of these parameters for the classification according to the Universal Soil Classification System (USCS) (7) and the one used in the highway area of the Highway Research Board (HRB) (8). As an additional characterization, the Sphericity and Roundness test has been carried out (Krumbein, 1940) (4).

On the sand, since it does not have a fine fraction, it has not been possible to carry out Atterberg Limits tests.

To assess the degree of compaction as a function of humidity, at fixed energy, Standard and Modified Proctor type compaction tests were carried out, in accordance with the American Society of Testing Materials (ASTM) standards, equivalent to the international standards of the American Association AASHTO, and those of the National Highway Administration (DNV) in Argentina.

The results obtained from the characterizations were the following:

-Particle Sieve Distribution analysis (PSD).

-Values obtained from PSD (MF/Cu/Cd).

-HRB (8) /SUCS (9) classification.

-Sphericity and Roundness

-Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) for Standard/Modified Proctor condition.

### SS21

For this tests, the chemical stabilizer used is HyGT SS21®, referred to as SS21 also in this document for reasons of simplicity. It is a polymeric type material, in aqueous solution, liquid, light amber in color, with a relative density with respect to water close to 1, and a slightly basic neutral pH, equal to 8.

The texture of the product is plastic, being used in water-solution for the tests in lab and for final use. It is used in percentage in water, being indicated in this way in the document, as % of SS21 and % of Water, together being the 100% of the solution. Therefore, the compaction water of the sands is partially replaced by a content of SS21, and the sands are then compacted with a solution of water + SS21.

SS21 has environmental approvals and has been determined to be an environmentally friendly product. Toxicity tests were carried out on the product through plant growth (IRAM 29114:2008) (1), heavy metal content tests such as Cadmium, Silver, Lead, Arsenic, Barium, Chromium, Mercury, obtaining environmentally satisfactory results.

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### Water and other materials

Water was used to dissolve the SS21, and form a solution. The dissolution was tested through the use of different types of water, with variation of its pH, salt content, and general parameters, determining that its effect has not produced significant variations. However, for the tests, distilled water was used, a common practice in the geotechnical laboratory.

No other materials were used during the development of the tests.

## Laboratory Testing

In this section, the mechanical tests carried out on the materials are detailed, both for Sand and for Sand+SS21.

### Sand Characterization

To characterize the sand, as detailed in section 2.1 of this document, the following tests were carried out, and results are detailed below.

#### Particle Sieve Distribution (PSD):

Sieve analysis test was carried out obtaining the following results:

**Table 1** Table of Sieves and accumulated percent

| Sand Characterization | | |
|---|---|---|
| Parameter | Value | Unit |
| Cu | 2 | - |
| Cc | 1 | - |
| MF | 1.590 | - |
| D10 | 0.160 | mm |
| D30 | 0.230 | mm |
| D60 | 0.390 | mm |

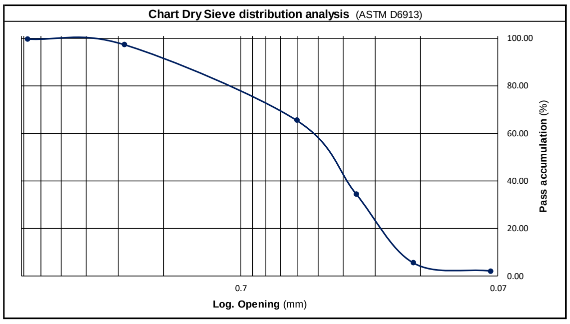



**Figure 2** PSD chart.

Following those results and calculations, the following parameters were obtained:

**Table 2** Values calculated from sieve analysis

| Sieve | | Pass Ac. |
|---|---|---|
| N° | (mm) | % |
| 4 | 4.750 | 99.91 |
| 10 | 2.000 | 97.58 |
| 40 | 0.425 | 65.60 |
| 50 | 0.300 | 34.72 |
| 100 | 0.150 | 5.67 |
| 200 | 0.075 | 2.19 |

Where:

- Cu= Coefficient of Uniformity
- Cc= Coefficient of Curvature
- MF= Modulus of Fineness
- D10,D30,D60= Diameter for passing 10,30 and 60% of sample respectively, obtained from the curve.

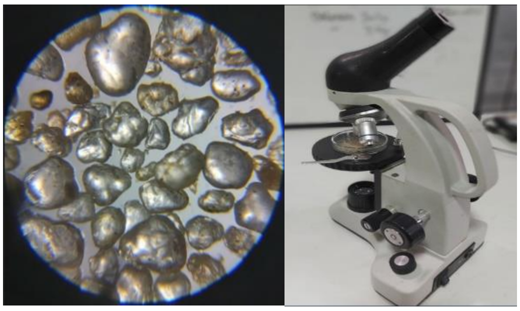
All these results follow the trend previously stated, of the hypothesis of a fine-grained sand with low to null fine content. Tested according to ASTM D 6913(3) standard.

**Figure 3** View of the tested sand.

#### Sphericity and roundness, Gs ,Si02 and classification (HRB/SUCS):

Sphericity and roundness parameters were obtained using a microscope and following the standard procedure.

Basically, a small sample of sand, usually 5 to 10g, is taken into an appropriate container and then placed on the microscope. The objective is to count 10 particles, and use them to consider their relative lengths X and Y, according to the Krumbein Chart ( See image 2.). The average values will be 2: 1st the Roundness, a measurement of how round shaped the particles are; 2nd the Sphericity, that is a measure of how close to a sphere the particles are. Sphericity and Roundness are dimensionless.



**Figures 4a and 4b** View through the microscope and microscope itself.

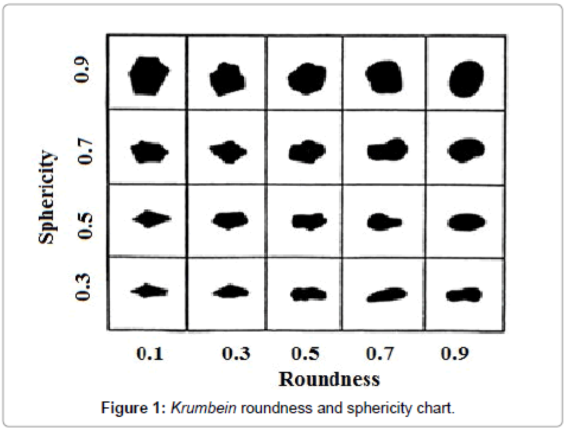



**Figure 5** Sphericity and roundness chart from Krumbein.

Gs value was obtained from a pycnometer test, and Si02 was reported from the sand supplier.

All the values are shown below:

**Table 3** Tests result.

| Sand Characterization | | |
|---|---|---|
| **Parameter** | **Value** | **Unit** |
| Round. | 0.7 | - |
| Sphericity. | 0.7 | - |
| SiO2 | 90-95 | % |
| Gs | 2.650 | g/cm3 |

Where:

- Round.= Krumbein's Roundness
- Sphericity= Krumbein's Sphericity
- Si02= Silica Content.
- Gs= Specific Weight of the solids.

Atterberg limits were not possible to be developed as the soil has nearly null fine content. The sand can be classified as following:

**Table 4** Classification of sand

| Sand Classification | |
|---|---|
| **Parameter** | **Value** |
| USCS | SP |
| HRB | A-3(0) |

.

Where:

- USCS = Unified Soil Classification System (ASTM D2487)
- HRB= Highway Research Board (ASTM D3282)
- SP= Poorly-Graded Clean Sand.
- A-3 (0)= Fine Sand, and group index 0 (ASTM D3282).

The aim of these tests is to quantify more properties of the sand and give more information about some characteristics of this particular Paraná Delta sand, for a deeper understanding.

As a final remark, we are in presence of a fine grained sand, with low to null fine content, rounded with medium sphericity and a mineralogy based mainly in quartz. No other particular points to note on this sand.

**Optimum Moisture Content (OMC) & Maximum Dry Density (MDD):**

The optimum moisture content (OMC) and de maximum dry density (MDD) are the main parameters for remoulded and compacted soils on field. Standard and Modified Proctor tests were done, following ASTM D 698 (5) and ASTM D 1557 (6) standards respectively.

Following results were obtained:

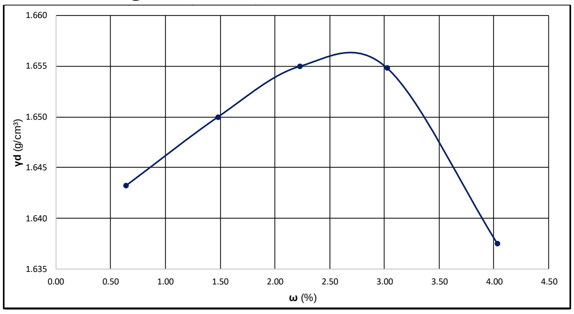



**Figure 6** Proctor Standard Test.

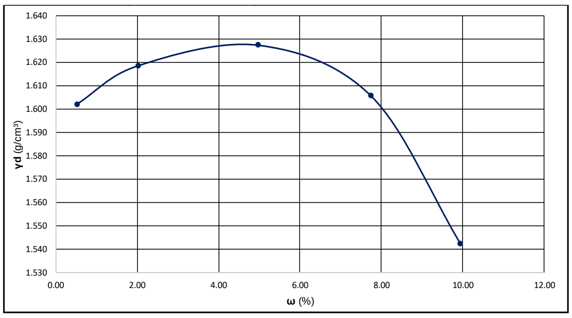



**Figure 7** Proctor Modified Test.

Where:

- X Axis stands for Moisture as a Percentage.
- Y Axis stands for Dry Density in g/cm3

**Table 5** Summary of PS and PM tests.

| Proctor | Standard | Modified | Unit |
|---|---|---|---|
| OMC | 4.9 | 3.0 | % |
| MDD | 1.628 | 1.656 | $g/cm^3$ |

**Unconfined Compressive Strength (UCS)**

Following the standard ASTM D 2166 (7), unconfined compressive strength tests were developed on remoulded samples compacted by the same methodology as Proctor tests, using increasing concentrations of SS21 in water as the compaction moisture solution.

Concentrations for the tests were 10, 20, 30, 40 and 50%, since without the addition of SS21 (0%), the sample is not able to self-stand because it does not have cohesion capacities.

These tests were carried out 72 hours after moulding the samples, with the aim of guaranteeing its drying, a point that is important for its performance, and that in the field is usually achieved in a much shorter time, but given the laboratory conditions and its presentation in moulds, the evaporation and/or drainage capacities are not the same.The preparation of the specimens was the standard practice, according to the preparation of samples during Proctor tests, at the OMC of the Proctor Standard test. They were made with a 4" mold, 2.54kg rammer with 575mm falling height, in 3 layers of 25 blows each layer.

**Figures 8a and 8b** Specimen with 20% solution of SS21, before being tested.

**Figure 9** Specimen with 20% solution of SS21, during test.

**Figure 10** Specimen after being tested.

Results are as follow:

**Table 6** UCS Tests Results. All tests results are summary of 3 samples each.

| SPECIMEN NAME | TYPE | γ (g/cm³) | γd (g/cm³) | ω (%) | UCS (N/mm²) |
|---|---|---|---|---|---|
| UCS-A1-4" | 10% SS21 | 1.735 | 1.668 | 4.02 | 0.236 |
| UCS-B1-4" | 20% SS21 | 1.757 | 1.693 | 3.78 | 0.906 |
| UCS-C1-4" | 30% SS21 | 1.753 | 1.696 | 3.39 | 1.586 |
| UCS-D1-4" | 40% SS22 | 1.695 | 1.641 | 3.31 | 1.841 |
| UCS-E1-4" | 50% SS23 | 1.723 | 1.670 | 3.20 | 2.124 |

Unconfined simple compression tests are considered in geotechnical engineering, both for road use and for foundations. These tests provide a clear and comparable reference to the load that the material can support in unconfined conditions, and it was particularly selected to assess the contribution that SS21 gives to the soil in its worst condition, that is, in sand in an unconfined condition. This allows valuing the potential and isolating the effect for its detailed study.

## California Bearing Ratio (CBR)

Following the standard ASTM D 1883 (10), CBR tests were performed, on Sand with the addition of water and SS21 in different concentrations.

Concentrations for the tests were 0,10, 20, 30, 40 and 50%, since for this test the mould gives enough confinement to the specimen.

Due to the condition of the sands, the unsoaked variant of the test was used, since the drained and non-drained behaviours would not have significant differences. On the other hand, the sand stabilized with SS21 acquires "Waterproof" properties both in mass and on the surface, and it is not designed to dry below the water table, so the physical phenomenon would be better represented in the unsoaked condition.

Specimens were made according to the usual sizes, 6" mould, 5,45kg rammer with 755mm falling height. Surcharge was lower than the minimum, 2,54kg, to force experiment into a more unconfined condition, a more exigent condition.

After the preparation of the specimens, an optimal time of 72h was determined to allow the drying of the product.

The specimens were tested by measuring load and displacement in a test press. The results obtained were the following:

**Table 7** CBR tests results summary. All tests results are summary of 3 samples each.

| SPECIMEN NAME | TYPE | γ (g/cm³) | γd (g/cm³) | ω (%) | CBR (%) |
|---|---|---|---|---|---|
| CBR-01-6" | 0% SS21 | 1.700 | 1.640 | 3.66 | 33.89 |
| CBR-A1-6" | 10% SS21 | 1.689 | 1.627 | 3.79 | 51.26 |
| CBR-B1-6" | 20% SS21 | 1.696 | 1.636 | 3.64 | 72.98 |
| CBR-C1-6" | 30% SS21 | 1.699 | 1.636 | 3.87 | 83.04 |
| CBR-D1-6" | 40% SS22 | 1.676 | 1.618 | 3.58 | 98.29 |
| CBR-E1-6" | 50% SS23 | 1.675 | 1.620 | 3.39 | 138.96 |

**Figure 11** Standard arrangement from WEG for CBR test showed on previous paper (16).

**Figure 12** CBR specimen removed from the mould and placed again to show the impressive results. The specimen has a 30% of OMC replacement with SS21.

**Figure 13** Fragment of sand stabilized with SS21. That sample is still under water, and at the moment is 1 year and counting. This is the live proof of the potentialities of SS21 for waterproofing and the justification for unsoaked condition approach. The specimen has a 20% of OMC replacement with SS21.

CBR tests are a type of test of considerable interest for road pavement engineering and geotechnics, and are spread worldwide. These provide a sort of relationship module between stresses and strains for a particular test condition, and given their extensive use internationally, they present a considerable amount of statistical information for making correlations. Although there are tests of a higher level of complexity and sophistication, CBR-type tests are easy to replicate in any road work field laboratory. On the other hand, it is a common language in geotechnical engineering at all levels of the hierarchy. These are the main reasons for their choice.

### 3.4 Brazilian Test Strength (BTS)

Following ASTM D 3967 standard, although it is for rock testing, the concept of the tests is the same. Basically, compressing across a diametral direction of the specimen, to obtain the tensile stress necessary to split the specimen.

As the case in the section 3.2, the tests were carried out in identical concentrations, with 72h of drying and identical compaction methods at optimum humidity.

The test uses the same procedure and specimen as UCS.

Results are as follow:

**Table 8** BTS tests results summary. All tests results are summary of 3 samples each.

| SPECIMEN NAME | TYPE | γ ($g/cm^3$) | γd ($g/cm^3$) | ω (%) | BTS ($N/mm^2$) |
|---|---|---|---|---|---|
| DIAM-A1-4" | 10% SS21 | 1.740 | 1.683 | 3.39 | 0.026 |
| DIAM-B1-4" | 20% SS21 | 1.790 | 1.731 | 3.41 | 0.054 |
| DIAM-C1-4" | 30% SS21 | 1.753 | 1.694 | 3.47 | 0.132 |
| DIAM-D1-4" | 40% SS22 | 1.774 | 1.715 | 3.42 | 0.263 |
| DIAM-E1-4" | 50% SS23 | 1.726 | 1.672 | 3.23 | 0.308 |

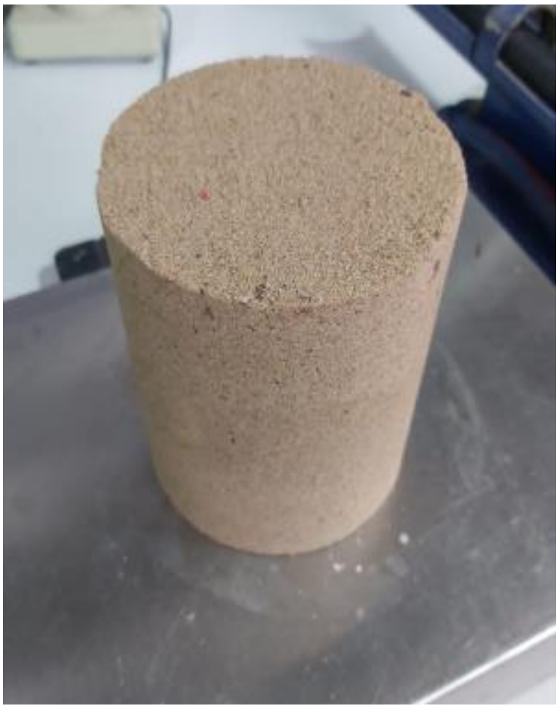


**Figure 14** Specimen before testing.

**Figure 15** Non formal test, developed with a car and the sample for an exhibition. The specimen was not broken after applying all the load.

This test is not so common in geotechnical engineering, and is mostly used for materials such as rocks or concrete. In this case, an attempt is made to demonstrate that SS21 provides tensile strength properties to the material, which generates an evolution of the floor towards a superior engineering material, with higher and more interesting properties for its various applications. In the case of roads, this would imply a radical improvement in their performance. On the other hand, the stability performance of this material would be greatly improved. The object of selection of this test is to compare the tensile strength of the material, in a properly unconfined condition, and isolate this behaviour, in order to obtain an assessment of the tensile strength provided by SS21.

In this way, the material obtained can be compared with mortars, concretes and other improved soils.

## Flexure and Compression tests

Following the ASTM D1635 (12) and ASTM C348 (13) flexure tests were carried out on specimens of 40x40x160mm and 100x100x350mm. The material was considered as improved soil and mortar, to provide a more broad and deep analysis.

For compression tests, ASTM C109 (14) was considered for 50mm side cubes, to work in addition to UCS tests. Compression tests were also developed over failed flexure specimens of 40x40x160mm, on beam sides.

No tests were developed at 10% in 40x40x160mm beams, as the strength was too small for testing at a hydraulic machine. Same for 10% and 20% in 100x100x350mm beams, because of the relative size.

Results were as follow:

**Table 9** Summary of results for flexure tests. All tests results are summary of 3 samples each. MR stands for Modulus of Rupture.

| SPECIMEN NAME | TYPE | SIZE | γ (g/cm$^3$) | γd (g/cm$^3$) | ω (%) | MR (N/mm$^2$) |
|---|---|---|---|---|---|---|
| FLEX C.1 | 30% SS21 | 100x100x350 | 1.659 | 1.617 | 2.60 | 0.164 |
| FLEX D.1 | 40% SS21 | 100x100x350 | 1.661 | 1.620 | 2.54 | 0.338 |
| Beams B1 | 20% SS21 | 40x40x160 | 1.734 | 1.658 | 3.27 | 0.061 |
| Beams C1 | 30% SS21 | 40x40x160 | 1.731 | 1.658 | 3.11 | 0.191 |
| Beams D1 | 40% SS21 | 40x40x160 | 1.788 | 1.735 | 3.06 | 0.355 |
| Beams E1 | 50% SS21 | 40x40x160 | 1.725 | 1.676 | 2.94 | 0.765 |

**Table 10** Summary of results of Compression Tests. All tests results are summary of 3 samples each.

| SPECIMEN NAME | TYPE | SIZE | γ (g/cm$^3$) | γd (g/cm$^3$) | ω (%) | σ (N/mm$^2$) |
|---|---|---|---|---|---|---|
| Beams sides B.1 | 20% SS21 | 40x40x40 | 1.734 | 1.658 | 3.27 | 0.29 |
| Cubes B.1 | 20% SS21 | 50x50x50 | 1.622 | 1.571 | 3.22 | 0.25 |
| Beams sides C.1 | 30% SS21 | 40x40x40 | 1.731 | 1.513 | 3.11 | 0.83 |
| Cubes C.1 | 30% SS21 | 50x50x50 | 1.561 | 1.513 | 3.14 | 0.76 |
| Beams sides D.1 | 40% SS21 | 40x40x40 | 1.788 | 1.735 | 3.06 | 1.47 |
| Cubes D.1 | 40% SS21 | 50x50x50 | 1.669 | 1.621 | 3.01 | 1.47 |
| Beams sides E.1 | 50% SS21 | 40x40x40 | 1.725 | 1.676 | 2.94 | 3.20 |
| Cubes E.1 | 50% SS21 | 50x50x50 | 1.687 | 1.636 | 3.17 | 2.77 |

**Figure 16** 100x100x350mm beam of sand with 30% of SS21.

**Figure 17** Beam on failure during test. 30% of SS21.

**Figure 18** Zoom on Beam on failure. 30% of SS21

**Figure 19** Beam during test. 30% of SS21.

**Figure 20** Preparation of specimens.

**Figure 21** Beam under failure during test. 20% of SS21.

These tests were selected to demonstrate the potential of SS21 for other applications. The results of these tests were useful for assess the flexural strength, that is correlated to the tensile strength. In conjunction with BTS tests, and Compression tests, a considerable well-correlated source of information is presented.

On the other hand, it is to assess the flexure-compression ratio relatively, and the tensile-compression ratio, to have a correlation that could be observed in other materials, being a pattern that usually describes points of interest in the behaviour of materials.

These results show the potential applications that this product provides in the field of geotechnical engineering.

## 4-Results and discussion

Results obtained show a considerable and consistent improvement of the sand mechanical properties, increasing as the concentration of SS21 increases.

To be noted as a reminder, the percentage of SS21 is percentage of replacement of the compaction water with SS21. Usually for this soils with moisture 3 to 5%, SS21 represents 0.9% to 1.5% of the total volume for a case of 30% of concentration.

The specimens reflect the capability of sands improved with SS21 to take tensile and flexure forces and to behave as a solid material, with a notable bonding force of adherence. Sand in natural condition and in unconfined compression are not able to take these forces, showing the improvement given by SS21.

### Compressive Strength:

Comparing the results obtained by compression tests, Cube tests from 50mm cubes or 40x40x160 flexure prism sides on compression, tend to give a higher value than the UCS tests. This can be attributed to a factor of scale and geometry. Also the densities and moistures are not the same, as well as the compaction is not given in the same way. UCS test are rammer compacted specimens, and prisms/cubes are locally compacted. In both cases the trend is upwards, and the compression values increases as the SS21 contents arises, giving a direct correlation between both. UCS values tend to be more conservative for higher contents of SS21 and more stable and linear. UCS values are recommended as a reference of compressive strength.

**Table 11** Improvement of the compressive strength of cubes comparing with 20% of SS21

| SS21 (%) | Compres. ($N/mm^2$) | Improv. (%) |
|---|---|---|
| 20 | 0.267 | - |
| 30 | 0.792 | 296.71 |
| 40 | 1.471 | 550.86 |
| 50 | 2.981 | 1116.62 |

**Table 12** Improvement of the compressive strength in UCS comparing with 10% of SS21.

| SS21 (%) | UCS ($N/mm^2$) | Improv. (%) |
|---|---|---|
| 10 | 0.236 | - |
| 20 | 0.906 | 384.42 |
| 30 | 1.586 | 673.16 |
| 40 | 1.841 | 781.35 |
| 50 | 2.124 | 901.56 |

**Flexure and Brazilian Tensile Strength (BTS) tests:**

To address and estimate the values of flexure and tensile strength, flexure and BTS tests have been performed.

The results are consistent and directly correlated to the increasing concentration of SS21.

**Table 13** Improvement of the tensile strength in BTS comparing with 30% of SS21.

| SS21 (%) | BTS ($N/mm^2$) | Improv. (%) |
|---|---|---|
| 10 | 0.026 | - |
| 20 | 0.054 | 207.69 |
| 30 | 0.132 | 506.23 |
| 40 | 0.263 | 1013.44 |
| 50 | 0.308 | 1184.36 |

**Table 14** Improvement of the flexure strength (Rupture Modulus) in beams comparing with 20% of SS21.

| SS21 (%) | MR ($N/mm^2$) | Improv. (%) |
|---|---|---|
| 20 | 0.061 | - |
| 30 | 0.177 | 289.81 |
| 40 | 0.347 | 566.13 |
| 50 | 0.765 | 1248.77 |

The BTS test gives a more soft variation, flexure test are more likely to experience more relevant improvement, in compressive strength, as SS21 concentration increases.

Comparing by dividing and multiplying by 100, the compressive strengths with the Flexure and tensile ones, the percentages are appreciable, and better than some other materials, for example concrete, that is in the order of 10 to 15%.

Flexure of beams over compressive strength for cubes and prisms sides is in the order of 23%. UCS over the BTS is in the order of 12%. These results are appreciable as a good ratio between tensile and compressive stresses. The usual value for concrete is between 10 to 15% in most of the cases.

**Table 15** Comparison between Flexure and compression strengths and Brazilian Test and Unconfined compressive strength. In percentage, to address the relative ratio between Tensile type of strengths with Compressive type of Strengths.

| SS21 (%) | Flex/Comp (%) | BTS/UCS (%) |
|---|---|---|
| 10 | N/A | 11.03% |
| 20 | 22.94% | 5.96% |
| 30 | 22.41% | 8.30% |
| 40 | 23.58% | 14.31% |
| 50 | 25.65% | 14.50% |

**California Bearing Ratio (CBR):**

CBR tests gave the possibility to compare with real sand values for 0% SS21 content and increasing in the same test condition. The results were considerably good in comparison, and gave an interesting perspective of the improvement given by the SS21.

**Table 16** CBR improvement comparing with 0% of SS21 (No SS21).

| SS21 (%) | CBR (%) | Improv. (%) |
|---|---|---|
| 0 | 33.89 | - |
| 10 | 51.26 | 151 |
| 20 | 72.98 | 215 |
| 30 | 83.04 | 245 |
| 40 | 98.29 | 290 |
| 50 | 138.96 | 410 |

**Table 17** Comparing CBR and UCS

| SS21 (%) | CBR (%) | UCS ($N/mm^2$) | CBR/UCS (-) |
|---|---|---|---|
| 10 | 51.26 | 0.236 | 217.55 |
| 20 | 72.98 | 0.906 | 80.57 |
| 30 | 83.04 | 1.586 | 52.35 |
| 40 | 98.29 | 1.841 | 53.39 |
| 50 | 138.96 | 2.124 | 65.41 |

Comparing both UCS and CBR with the expressions given by the author in previous publications (16):

$$UCS = -0.426 * (CBR)^2 + 2.212 * (CBR) \text{ (Ex.1)}$$

**Figure 22** Expression 1

And:

$$CBR = 0.56 * UCS^{1.07} \text{(Ex.2)}$$

**Figure 23** Expression 2

Considering the original expressions are in kgf/cm2 instead of N/mm2, the values were adjusted.

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**Table 18** Estimation of UCS and CBR based on Expressions 1 and 2.

| SS21 (%) | UCS ($N/mm^2$) | UCS Ex1 ($N/mm^2$) | ΔUCS (%) | CBR (%) | CBR Ex2 (%) | ΔCBR (%) |
|---|---|---|---|---|---|---|
| 10 | 0.236 | 1.002 | 76.49 | 51.26 | 14.31 | -258.30 |
| 20 | 0.906 | 1.361 | 33.43 | 72.98 | 60.43 | -20.76 |
| 30 | 1.586 | 1.513 | -4.82 | 83.04 | 110.06 | 24.55 |
| 40 | 1.841 | 1.729 | -6.51 | 98.29 | 129.09 | 23.86 |
| 50 | 2.124 | 2.208 | 3.78 | 138.96 | 150.45 | 7.64 |

Expression 1 gave a good fit for the case, between 3.78% and -6.51%, a range of 10.29 points but a ±5.14 points for the range 30 to 50%. For 10 and 20% of SS21, the correlation is disperse.

Expression 2 was not as accurate as expression 1, with a range between 7.64 and 24.55 points, for 30 to 50% of SS21 overestimating CBR values. For 10 and 20% of SS21, the correlation is disperse.

Using the chart and the values, considering a preliminary formula for a quadratic relationship between CBR and UCS, the following expression can be considered:

$$CS = -0.0018 * (CBR)^2 + 0.4928 * (CBR) - 12.488 \quad (Ex.3)$$

**Figure 24** Expression 3

Considering the original expressions are in kgf/cm2 instead of N/mm2, the values were adjusted.

The values obtained with the expression:

**Table 19** Estimation of UCS based on CBR data.

| SS21 (%) | CBR (%) | Est.UCS ($N/mm^2$) | UCS ($N/mm^2$) | ΔUCS (%) |
|---|---|---|---|---|
| 10 | 51.26 | 1.002 | 0.236 | -325.33 |
| 20 | 72.98 | 1.361 | 0.906 | -50.21 |
| 30 | 83.04 | 1.513 | 1.586 | 4.60 |
| 40 | 98.29 | 1.729 | 1.841 | 6.11 |
| 50 | 138.96 | 2.208 | 2.124 | -3.92 |

Ex.3 expression is more accurate, and can be useful for a general approach of SS21 on sands for this case. Expression 1 was considered accurate enough for the case. For 20% and 10%, the correlation was disperse.

Following, all the charts related to the above will be presented:

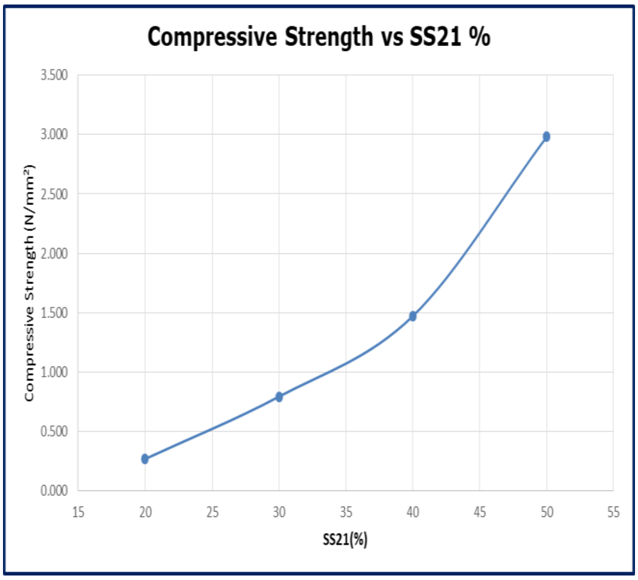


**Figure 25** Chart of Compressive Strength vs SS21%.

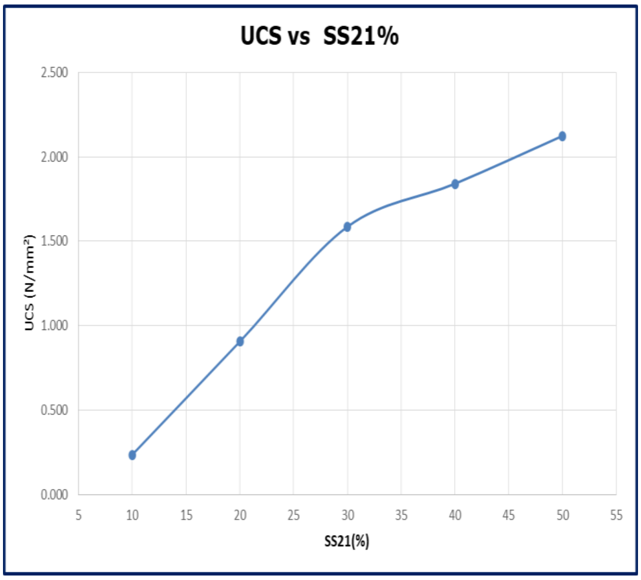


**Figure 26** Chart of UCS vs SS21%.

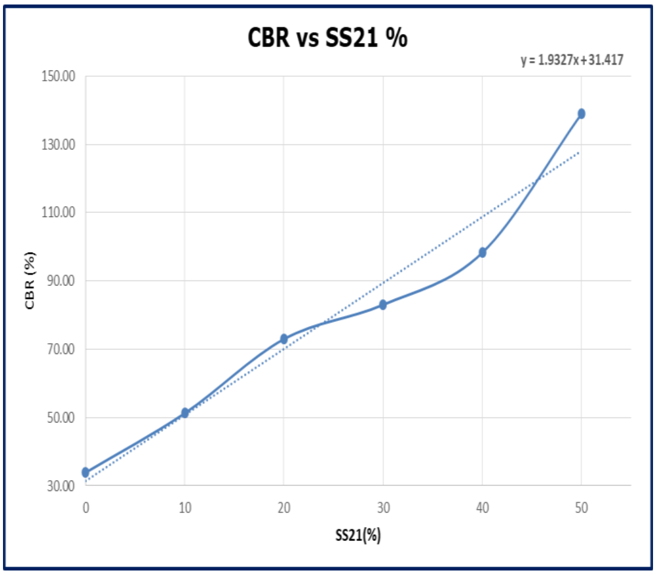


**Figure 27** Chart of CBR vs SS21%

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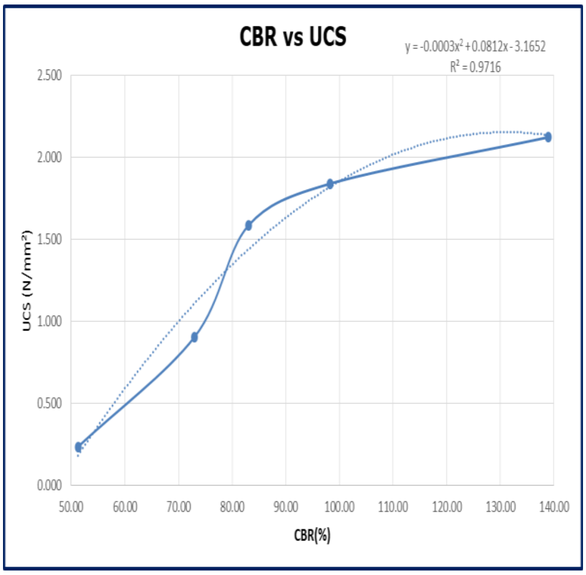


**Figure 28** Chart of CBR vs UCS

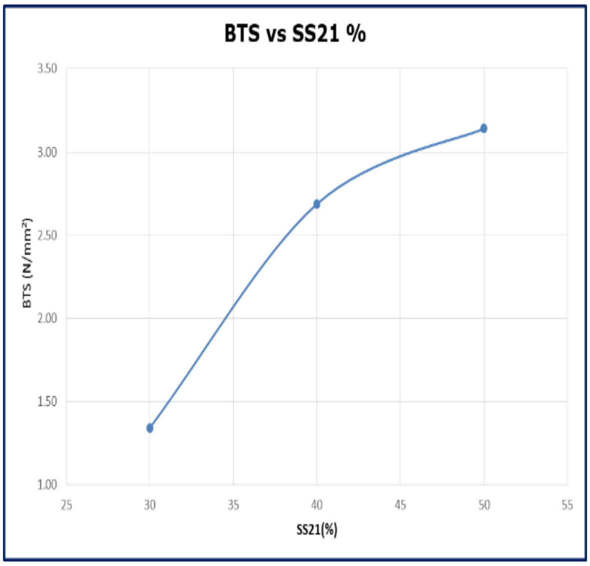


**Figure 29** Chart of BTS vs SS21%

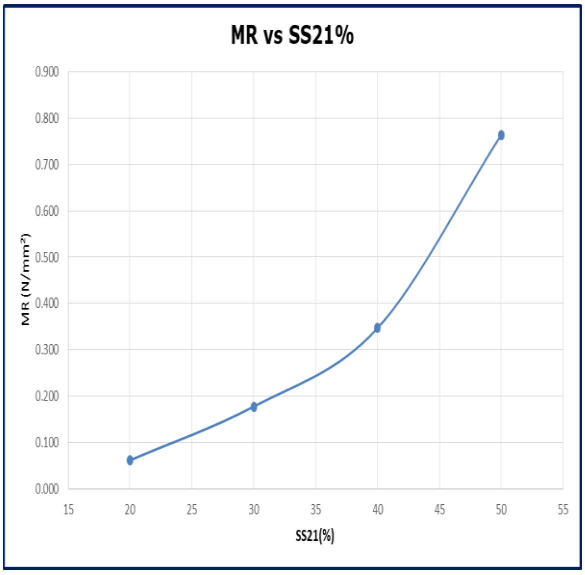


**Figure 30** Chart of MR vs SS21%

## Conclusions

The objectives of the present study have been achieved, with a sufficient characterization of the effect of SS21 on sands of the Paraná River Delta in Argentina, with a main focus on its road use, but with more tests, relationships, variables and parameters that can be useful for other uses.

It can be considered that the performance of SS21 for the stabilization of granular soils, in this case sandy, is highly effective and presents notable benefits in soil properties.

Is shown, that the improvement starting from a sandy soil is relevant, highlighting the importance of the fact that this is an analysis in the worst condition, which is unconfined condition and of a purely frictional material with low to null content of fines. These points allow SS21 to be valued as a material that provides a quality differential in soil engineering properties.

The potentialities provided by the SS21 are not limited solely to the road environment. The performance underwater, waterproofing and the reduction of permeability, as well as its adhesion, give it interesting properties to be used in the dust-control and erosion. This grants a considerable contribution to infrastructure, oil and mining works in terms of mainly geotechnical works.

Traditional soil stabilization processes are challenged by a substantial improvement provided by the ease of using a liquid stabilizer, easy storage and high performance.

All these conclusions are justified on the scientific basis of a wide variety of laboratory tests with results of relevant interest.

The SS21 solution for sands in the condition of roads, embankments and slopes is demonstrated through the tests and results presented in this document.

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## Conflicts of interest

There is no conflict of interest and the information provided is true and generated by the authors.

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