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Evaluation of Tensile Strength Testing of Fiberglass and Steel Rebar in Nailing of Tunnel Excavation Fronts in Soil Masses

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Abstract: This work presents a study of the behavior of fiberglass in its application as a reinforcement element in the containment of soil masses in the form of rebar and a comparison with respect to steel for the same application. It was designed from the results of tensile strength tests performed with fiberglass and steel rebar and the development of a statistical study to increase the accuracy of the results, obtaining more refined information about the actual conditions of differentiation and a concise determination of the presented advantages of one material with respect to the other as to its tensile strength. It would be possible to perform the statistical study using the Normal (Gauss curve) standard, which considers the mean and standard deviation values as the global values for both materials. However, due to the reduced number of available specimens, the t-Student test standard was used for executing a comparative analysis between the groups. This is based on the mean and standard deviation of the results obtained for the samples to compare the average tensile strength of both materials globally. The results allowed affirming that the fiberglass rebar presents tensile strength at rupture with statistically significant superiority in relation to the steel rebar.

Key words: fiberglass, nailed soil, rebar, steel, tensile strength tests

1. Introduction

Since over four thousand years ago, tunnels were excavated in European mountains for the extraction and transport of gold, copper and salt. In this context, their execution was performed with the use of manual instruments in a slow and difficult way. Technological development over the centuries has promoted not only the development of more productive excavation methodologies, but also the increasing demand for new roads, especially by land, both for the transportation of materials and people. Currently, several road infrastructure works require the opening of underground passages in order to avoid major environmental, socioeconomic and urban impacts, especially in large urban centers.

According to the composition of the soil of certain slopes or soil masses to be drilled, it is necessary to use special containment systems for the walls of the tunnels during the excavation phase to prevent their collapse as a consequence of the reduction of soil containment stress during the execution of such services. The nailed soil is a system of containment of soil masses quite common in the construction sector. Such technique is based on soil reinforcement by the introduction of composite bending resistant elements called “clamps”, which may be steel bars, synthetic bars, micro-stakes, or even stakes. The clamps, or rebar, are installed horizontally or with a certain vertical inclination to introduce tensile stresses, shear forces and bending moments. Such rebar can be made up of various

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materials, such as steel (more traditional), carbon fiber and fiberglass. The latest presents some favorable properties, such as high mechanical strength, tensile strength superior to almost all metals, reasonable impact resistance, low water absorption, and chemical resistance to most microorganisms. Fiberglass rebar is still rarely used in Brazil. In several European countries, however, the scenario is reversed as the material is immune to corrosion, which encourages its use mainly in regions subjected to periods of intense snow.

2. Bibliographic Review

2.1 Introduction

The first known tunnel in Brazil began to be executed in early 1948, when geologists were hired to study the opening of the Santa Cecilia tunnel excavated by Light Company in Rio de Janeiro. As an example of a totally underground subway line, it can be mentioned, among other cases, the Line 2 of the São Paulo subway, in particular the Brigadeiro and Trianon-MASP Stations, built under Paulista Avenue in places with very low ground cover (only 4 meters). During construction works, vehicular traffic did not have to be interrupted for a single day. Fig. 1 shows a perspective of the Brigadeiro and Trianon-MASP Stations, illustrating their three-dimensional layout.

2.2 NATM Method

NATM, acronym for "New Austrian Tunneling Method", is a method of excavating tunnels developed between 1957 and 1965 by the Austrian Professors Landislau von Rabcewicz, Leopold Muler, and Franz Pacher, created from the Austrian method ATM (Austrian Tunneling Method), which consisted of the application of temporary wooden struts for the excavation of the full section, followed by the definitive supports. The ATM presented certain negative points, such as the use of large amounts of wood in the execution of the provisional shoring of the walls of the soil mass and the excessive settlements. Those issues would be rectified with the NATM, in which the use of rebar and concrete layer projected in the front of excavation does not require the use of other materials for shoring. Through the new method, it was possible to alleviate the tensions and to allow the deformations, controlling them when necessary.

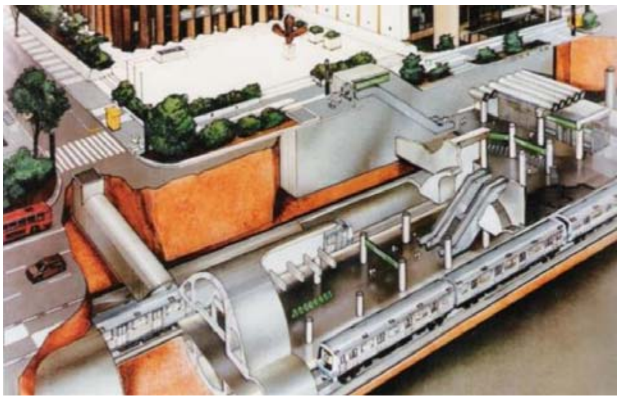

Fig. 1 Perspective of Brigadeiro and Trianon-MASP subway stations [1].

NATM is considered a sequential method of excavation, as its constructive process follows a cyclic sequence based on the following steps: excavation of the mass, cleaning in the front of excavation, installation of the support system and adoption of auxiliary constructive measures. After the excavation, a layer of coating is executed with projected concrete, metallic screen, cranksets and short anchors to stabilize the own weight of the soil and its tensions. According to Shlosser (1991) [2], the anchors are arranged from 3 to 6 meters apart along the gallery, and can be inserted into the soil through two techniques: percussion or drilling with the injection of cement laitance. Such method is considered quite flexible. Through auxiliary measures and resources for the design, construction and treatment of the soil mass, it is possible to apply it to tunnel excavation in practically any soil condition, and through any obstruction, including deep foundations. This is also true for the excavation in large underground works, such as subway stations with minimal coverage, in a way there is no impact on the surface (there would be major disturbances if the open-air excavation method was used). With NATM, the currently available features allow to excavate any type of soil safely.

In Brazil, it is possible to mention as an example of application of the NATM method the Imigrantes Road, which is an important link between the capital and the coast of São Paulo, mainly with the Port of Santos. This work was carried out in two stages: the ascending runway (1969-1975) by Road Development — DERSA and more than 20 years later, the downhill runway (1998-2002) by ECOVIAS, already under the concession program. The uphill runway project envisaged the execution of a succession of tunnels and viaducts, restricting cuts that could alter the natural balance of the slopes, which made the construction of service roads and access to the tunnels the most critical point of the works. After researching new techniques and construction processes that, together with safety, brought greater productivity, profitability and flexibility for construction, the method was introduced in Brazil, which represented a great historical landmark for the opening of tunnels in the country.

The Northern section of the RODOANEL was also executed according to the NATM, this time with fiberglass rebar replacing traditional steel, due to he cleaning of the excavation front being clearly facilitated with the usage of that material after the rock explosion. In the case of steel, a tangle is formed among the bars, which later requires the cutting of the bars individually with blowtorches. For fiberglass, the lead time is significantly reduced because its clamps are easily broken by the tunneling machinery itself.

As for the material itself, the first time fiberglass rebar was used as reinforcement in front of tunnel excavation was in 1895, in the tunnels of the high-speed railway linking Rome to Florence, in the section known as Florence-Arezzo. This region presents low quality geological formations, a mixture of clayey and sandy soil and several submerged stretches, which caused considerable difficulties during the construction, and even the collapse of one of the stretches, leading to the interdiction of the work and the elaboration of new projects for the tunnels [3]. The tunnel connecting Florence and Arezzo was transformed into a huge experimental building. The fiberglass reinforcements allowed the excavation of the whole front, giving a concave form to the cavity, and hence favoring the natural production of a longitudinal arch effect. The first experiments were based on the following parameters [3]:

- Length of each reinforced section: L = 15 m;
- Diameter of fiberglass rebar: ø = 60/40 mm;
- Overlap between the reinforced sections: S = 5.

Fig. 2 illustrates an implementation scheme of this system.

2.3 Fiberglass

The production of glass fibers began about 2300 years ago in the Mediterranean region, near ancient Syria, Greece and Egypt. Craftsmen at the time began to produce the fibers through heated glass rods to apply it as a relief on the surface of finished products. Commercially, fiberglass began to be developed in the year 1939, during World War II, with the purpose of providing rigidity to the military equipment. Today, glass fibers are applied in more than 35,000 products in nearly all industrial segments. These are obtained from a mixture of oxides of Si, Al, B, Ca and Mg, and are usually used as reinforcements for thermoplastics due to their low cost [4].

In general, glass fibers have several advantages compared to other polymeric composites, which justifies the fact that this is the most used material among them, i.e., its high mechanical strength, superior tensile strength to almost all metals, significant impact resistance, low water absorption, chemical resistance to most microorganisms, low coefficient of thermal

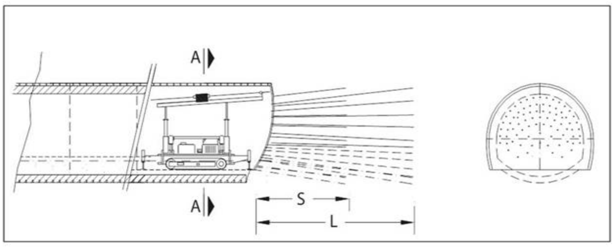

Fig. 2 Positioning of rebar sections at the longitudinal and vertical of the Florence-Arezzo Tunnel [3].

expansion, excellent electrical properties, incombustibility, and the possibility of obtaining translucent materials. This type of material is composed of glass filaments of reduced thickness, which are aggregated through applications of resins, silicones, phenols and other compounds soluble in organic solvents. It also receives another catalyst substance that may contain oxides of potassium, iron, calcium and aluminum [5].

There are several groups of glasses composed of different types of raw material, but silica is considered the most important for use in composites. According to Matthews and Rawlings (1994) [6], the fibers are easily produced by heating the glass and by gravitationally casting from a platinum mandrel. The mandrel contains approximately 200 channels, and then 200 fibers of 10 micron diameter are made simultaneously. Glass fibers are generally 5 to 20 microns in diameter, and their surfaces are not free of faults and may be intrinsically associated with irritations on the human skin [7].

As a new way of using fiber, fiberglass rebar is produced with excellent mechanical properties that allow distinct applications within civil construction.

It is important mentioning the care to be taken with the handling and storage of the material, which must be stored away from the ground to avoid contamination with waste, and always handled by specialized personnel and with the use of Personal Protective Equipment, especially gloves, to avoid injuries or skin problems in the hands. As an example of its use, it can be mentioned the “Praia do Futuro” Beach in Fortaleza, Brazil. The site is the second most affected area by the sea and saline pollution in the world, behind only the Dead Sea region in Israel. In these places, the corrosion rate is very high, which can be harmful to the use of steel in constructions, mainly buildings. Because fiberglass has excellent chemical resistance, this has often been used as an option to solve such adversity.

3. Material and Methods

Tensile strength tests were carried out for steel and fiberglass rebar in order to compare their respective mechanical characteristics, in particular their tensile resistance.

These tests were carried out in a laboratory by the company TESTIN, with subsequent emission of technical report to document the results obtained. For this purpose, a universal test machine was used and, for the purpose of standardizing the results, 50 cm long and 12.5 mm diameter rebar were tested for both materials. However, due to the uniqueness of the fiberglass rebar still used in Brazil, the equipment used does not yet have the basic requirements for the proper execution of such test, especially with regard to the fixation devices of the specimens at their ends, which should be positioned so as not to interfere with the tests, as well as with the results further presented. Therefore, to make feasible the preparation of a comparative study between the two materials, adaptations were made at the ends of the fiberglass rebar in order to guarantee the accuracy of the proposed comparison, as shown in Fig. 3.

3.1 Test Method

The tests were performed according to the Brazilian standard NBR ISO 6892-1, which determines the factors to be considered in tensile tests for metallic materials. The same standard was used for both materials, since fiberglass was not regulated by the Brazilian Association of Technical Standards until the present moment. To obtain the resistances corresponding to the tested materials, the analyzed specimens were subjected to axial tension until their

Fig. 3 Glass fiber specimen **model.**

ruptures were reached. Five steel specimens and six glass fiberglass specimens were tested, as shown in to Figs. 4 and 5, respectively.

For an accurate determination of the deformations verified in the test with the steel specimens, a strain gauge with millimetric precision was attached to the bar during the application of tensions within its nominal range of elastic regime, as shown in Fig. 4. Due to its physical properties, fiberglass has very close values of flow and rupture stresses, which indicates that the material presents a range of stresses within the plastic regime significantly reduced in relation to steel. In this way, the deformations are practically imperceptible before the rupture stress is reached. In addition, the lack of information about the material does not allow a precise estimate of an average nominal

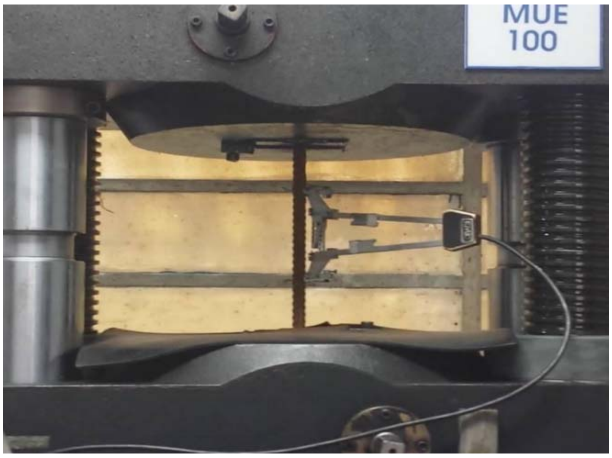

Fig. 4 Steel specimen during execution of tensile strength test.

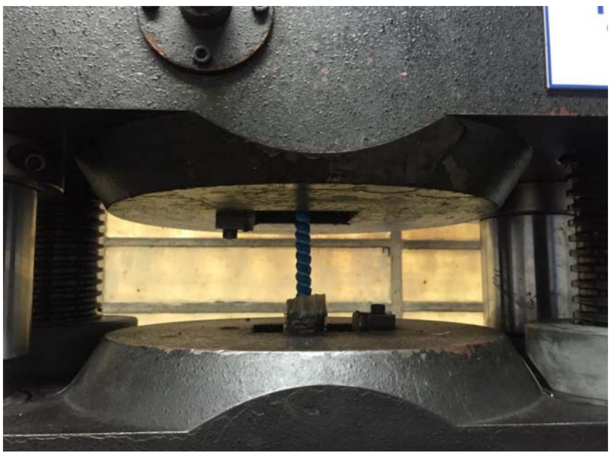

Fig. 5 Fiberglass proof body during realization of tensile strength test.

value of these stresses, which was decisive for the option of not using the strain gauge in this case, since it could suffer irreversible damages during the rupture of the specimen. Lastly, as previously seen, the very necessary adaptation for the proper functioning of the test equipment in the case of fibers limits the visible region of the specimen laterally, which also makes it impossible to attach the device to the specimens during the analysis.

4. Results and Discussion

4.1 Types of Rupture Verified

The higher ductility of the steel in relation to the fiberglass can be visualized in the realized tests. Although for a short time, the area of the specimen section was slightly reduced at its weakest point just before its rupture was reached, as indicated in Fig. 6. The same deformation does not occur in the case of the fiber, which breaks without presenting significant or visible deformations (Fig. 7).

4.2 Test Results

Table 1 shows the results of tensile tests with samples of glass and steel rebar.

The results of the steel rebar test were considered to be consistent.

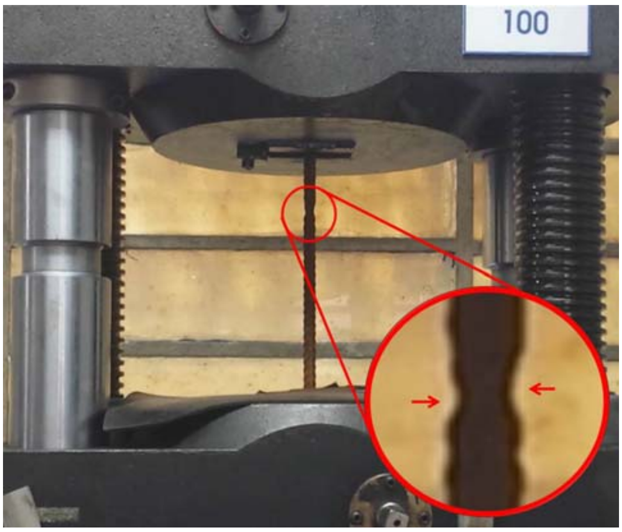

Fig. 6 Deformation of the cross section of the steel during fragile zone testing.

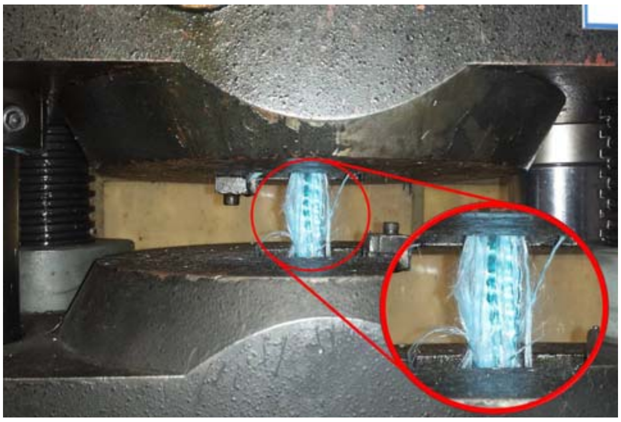

Fig. 7 Rupture of the fiberglass in a tensile strength test.

Table 1 Resistances in rupture measurements in tensile strength tests.

Specimen	Resistance to rupture – steel (MPa)	Resistance to rupture – fiber of glass (MPa)
1	654,0	753.4
2	663,9	**553.8**
3	648,8	973.6
4	655,9	913.5
5	653,7	915.3
6	-	**635.7**

Regarding the results of the test with fiberglass rebar, the specimens 2 and 6 were disregarded in the statistical evaluation, since n. 2 presented a failure in the fixation system during the test and n. 6 presented a different behavior in the rupture features. In the other specimens, the fibers were gradually broken according to the increase in tension, culminating in a "maximum rupture" when the rupture stress was reached, in which not only the breaking of the remaining fibers could be visualized, but also the resin layer ruptured thereon. In specimen 6, the resin layer broke before the tensile strength was reached, and therefore, even when this tension was reached, there were still fibers that had not been ruptured, which led to disregard this result in the study.

4.3 Statistical Evaluation of Test Results

Table 2 presents a descriptive summary of the results of the test, in descriptive statistics, in which it is noted that, despite a greater variability for the fiberglass tested sample, both in mean and median values, the rupture stress of this material exceeds the results of the steel sample.

The confidence intervals were composed to estimate the true mean value of rupture of fiberglass and steel. In Table 3, it can be seen that the average steel rupture stress is some value between 648.4 MPa and 662.1 MPa (with 95% probability), whereas for glass fiber the true average value of the resistance is in the range between 738.5 MPa and 1039.4 MPa, with the same probability. The fact that the variation range is high in this case is motivated by the high variability observed in the regarded sample.

Fig. 8 presents the above data. Y axis corresponds to rupture stress in kgf, for the tested specimens (diameter 12.5 mm).

Table 2 Summary of results from descriptive statistics tests.

Parameter	Steel rebar	Fiberglass rebar
Sample– N	5	4
Mean (MPa)	655.2	889.0
Standard deviation	5.5	94.6
Coefficient of Variation (%)	0.84	10.64
Median (MPa)	654.0	914.4

Table 3 Range of variation for a confidence interval (CI) of 95% in the samples of steel and fiberglass.

Parameter	Steel rebar	Fiberglass rebar
Sample - N	5	4
Standard error Mean (MPa)	2.5	47.2
CI-95% (MPa)	648.4-662.1	738.5-1039.4

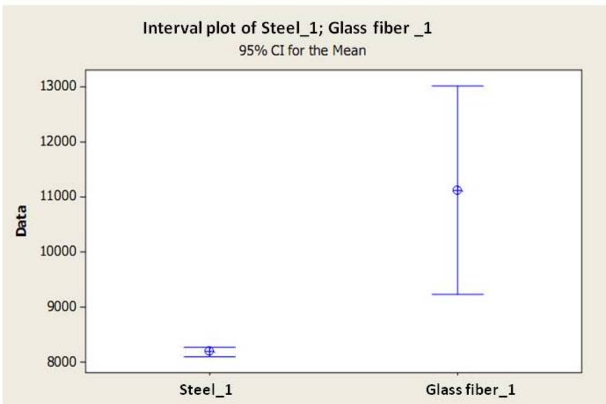

Fig. 8 Graph of the 95% confidence interval for steel and glass fiber samples.

Finally, a comparison of the mean rupture stress between the two materials was performed using the t-Student test for two independent groups. In the samples, an average difference of approximately 232 MPa was observed in favor of fiberglass, which statistically represents a highly significant difference (p-value = 0.008). The p-value represents the probability of erroneously concluding that fiberglass features a tensile strength higher than steel, i.e., concluding that fiber is better than steel when in fact it is not. The statistical procedure tolerates a probability of 5% of the decision taken to be wrong. Therefore, if p-value is less than 5% (significance level), the error is in the acceptable range for the test, being in this case the decision that fiber is better than steel a coherent conclusion. The value found for the index (0.8%) is much lower than the significance of 5% (CI = 95%).

The same study was performed once again considering the value of specimen 6 of fiberglass, discarded in the previous analysis. The value found for the index was of 2.1%, which is also lower than the significance of 5% (CI = 95%).

5. Conclusions

The tests performed with the objective of comparing the behavior of steel and fiberglass rebar, as well as the statistical study proposed following the results, allowed to state that the glass fiber presents a tensile strength with statistically significant superiority to that of steel. This is ensured by the results obtained for the variable p-value, which presented statistically representative values.

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