

Strengthening of 3D Printed Tunnel Linings with Bolts and Geogrid Based on NATM Approach

Kucuk Ilayda Bengisu¹⁾, Evirgen Burak¹⁾

¹⁾Eskisehir Technical University

DOI: <https://doi.org/10.3217/nqr3b-rym33>



1 Introduction

Laboratory testing occupies a fundamental role in determining the in-situ performance of structures and verifying design criteria. Experiments performed either on individual elements or directly on the design itself help to anticipate and mitigate adverse behaviors and deficiencies that may manifest in field conditions. Nevertheless, reproducing detailed components of experimental setups using conventional methods is often challenging. Therefore, the rapid advancement of three-dimensional (3D) printing technology has advantages such as the ability to realize complex geometries, accelerated prototyping, cost efficiency, and customization.

In rock mechanics, where the sampling of specimens is remarkably difficult, Jiang et al. (2016a) demonstrated that combining laser scanning with 3D printing improves specimen reproducibility, even in the presence of cracks. Subsequent studies reported that PLA-based specimens exhibit mechanical behavior closer to ductile materials than to brittle rocks (Jiang et al., 2016b; Song et al., 2018). To address this limitation, Song et al. (2018) investigated gypsum powder as a printing material and showed that its stress–strain response more closely resembles the behavior of natural rocks. The further extended 3D printing applications to tunnel modeled as reference, single-fault, double-fault, and rock-bolted tunnel models using gypsum powder for tunnel bodies and PLA for bolts. The reference and single-fault tunnels exhibited deformation and fracture patterns comparable to artificial models, while the results confirmed that rock bolts and linings significantly enhance tunnel load-bearing capacity, whereas faulting harmfully affects stability. These findings prove the efficiency of 3D printing for producing reliable physical models of complex tunnel systems. By the way, in this study the simultaneous effect of geogrids and bolts in tunnel lining systems under weak soil conditions were investigated, within five tunnel configurations including variable lining thicknesses and reinforcements via 3D-

printed geogrids and bolts. The study proposes an alternative lining concept for NATM applications.

2 Materials and Methods

2.1 Design of Tunnels, Geogrids, Bolts and Preparation of Specimens

For the 3D-printing process, ABS (acrylonitrile butadiene styrene) filament was selected for tunnel and bolt production due to its relatively higher strength, while PLA (polylactic acid) was used for geogrids since serving greater ductility. Although tunnel and bolt geometries were scaled by 2.0 according to Song et al. (2018); the bolts were redesigned with wings to enhance the pullout capacity as an anchorage. Each tunnel measured 10 cm in length, 8 cm in width, and 7 cm in height, with wall thicknesses varying from 1 to 4 mm. Two geogrids were designed to be flat and unidirectional. Tunnels were confined along lateral direction with resin-coated original bidirectional glass and polyester geogrids, as well as 3D-printed flat and unidirectional geogrids in addition to the reference ones. Ten bolts were applied on the tunnel lines as well as were reinforced with 3D-printed unidirectional geogrids.

Even though concrete molds were assembled using ABS filament via 3D printing, unexpected strong adhesion between the concrete and molds prevented demolding. So, RTV-2 silicone molds were produced. Owing to the thin tunnel walls, successful demolding was achieved only for 10 mm-thick specimens. Concrete mixtures were prepared using pozzolanic cement (32.5 N) and silica sand, with optimized water-to-cement (w/c) and cement-to-sand (c/s) ratios of 0.5. Three concrete tunnel specimens were produced to be unreinforced reference ones, a glass fiber geogrid-confined tunnel, and a polyester geogrid-confined tunnel. In addition, three cylindrical concrete specimens (36 mm in diameter, 72 mm in height) were tested under uniaxial compression tests to obtain the compressive strength of concrete.

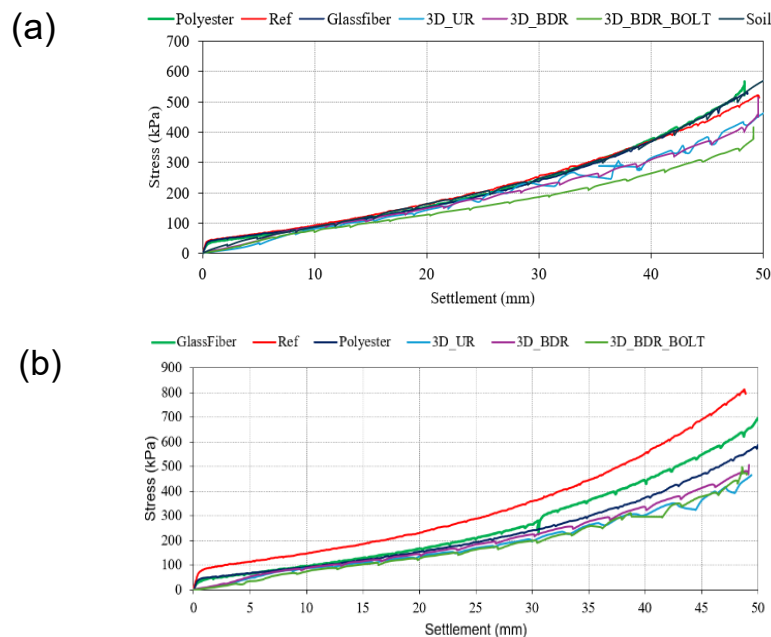
2.2 Experimental Apparatus and Soil Properties

The main geotechnical parameters of soil, which contains the 75% silica sand and 25% silty clay, were found to be specific gravity of 2.59, plastic limit of 43.3%, optimum moisture content of 11.67%, internal friction angle of 38.73°, and cohesion of 5.4 kN/m². Experiments were conducted in a steel test cell with dimensions of 40×40×10 cm. For visual monitoring plexiglass windows were installed at the midportion and strain gauges were installed on the right-side wall and the crown of tunnel linings. Before testing, a preload of 2kN was applied to achieve a standard relative soil density of 65%.

3 Results and Discussion

UR, BDR, and BDR_BOLT denote unreinforced tunnels, unidirectionally geogrid-reinforced tunnels, and tunnels reinforced with both unidirectional geogrid and bolts at the same time as seen in the curves of the uniaxial loading tests (Fig.1). According to coupon tests, the average tensile strength values of ABS and PLA filaments were 24.35 kN/m and 3.18 kN/m (Güleç and Evirgen, 2023) as well as polyester-based geogrid-coated and glass fiber geogrid-coated coupons were determined to be 44.30 kN/m and 105.50 kN/m, respectively.

Tunnel stiffness increased with wall thickness, resulting in faster settlement responses in general. An additional test on unreinforced soil was conducted for comparison. For 1 mm-thick tunnels, glass fiber, polyester, and reference specimens exhibited similar behaviors, with settlements and strengths of 48.38 mm–521.49 kPa, 48.65 mm–527.32 kPa, and 49.66 mm–513.99 kPa, respectively. At 2 mm thickness, the glass fiber specimen reached 880 kPa at 51.11 mm settlement, The polyester specimen failed at 28.66 mm settlement and 304.07 kPa. For 3-4 mm tunnels, reference specimens exhibited higher strengths than the geogrid-reinforced specimens but failed at similar settlement levels. At 4 mm thickness, values increased to 1698 kPa (reference), while glass fiber and polyester specimens reached 519.83 kPa and 464.84 kPa, respectively. The maximum improvement ratio of 119.17% was observed for the 2 mm tunnels. For 3D-printed geogrids, unidirectional reinforcement provided higher strength than flat geogrids. In contrast, specimens reinforced with both geogrids and bolts exhibited reduced strength (351.55 kPa at 47.94 mm), likely due to misalignment. Geogrid reinforcement proved most effective for thinner tunnel linings, particularly at 2 mm tunnels. Bolt-reinforced specimens consistently exhibited lower performance, indicating the need for further optimization of design or installation.



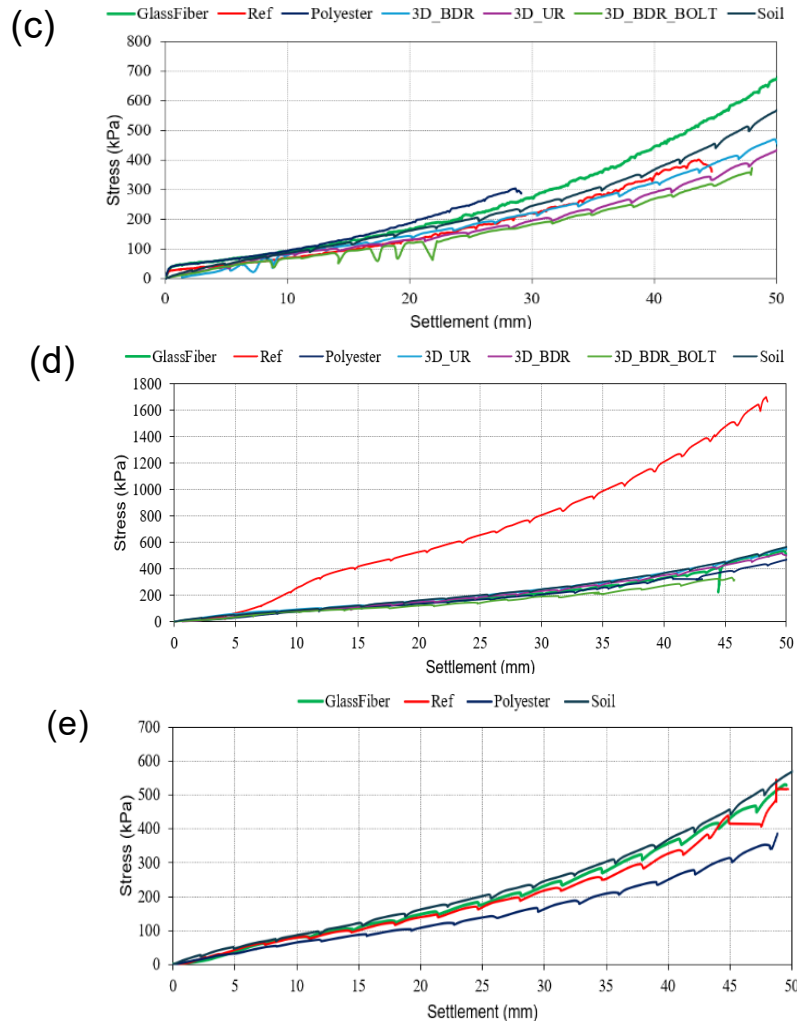


Fig. 1: Uniaxial loading test results for tunnels wrt. thickness; (a) 1 mm (b) 2 mm; (c) 3 mm; (d) 4 mm; (e) uniaxial test results for concrete tunnels

4 References

- Güleç E., Evirgen, B., 2023. A scale effect on the geogrids produced with three-dimensional printer technology. *J Fac Eng Archit Gazi Univ* 38, pp.1793–1803, DOI:[10.17341/gazimmfd.909508](https://doi.org/10.17341/gazimmfd.909508).
- Jiang Q., Feng X., Gong Y., Song L., Ran S., Cui J., 2016a. Reverse modelling of natural rock joints using 3D scanning and 3D printing. *Comput Geotech* 73, pp. 210–220, DOI:[10.1016/j.compgeo.2015.11.020](https://doi.org/10.1016/j.compgeo.2015.11.020).
- Jiang Q., Feng X., Song L., Gong Y., Zheng H., Cui J., 2016b. Modeling rock specimens through 3D printing: Tentative experiments and prospects. *AMS PRC* 32, pp. 101–111, DOI:[10.1007/s10409-015-0524-4](https://doi.org/10.1007/s10409-015-0524-4).
- Song LB., Jiang Q., Shi YE., Feng XT., Li Y., Su F., Liu C., 2018. Feasibility investigation of 3D printing technology for geotechnical physical models: study of tunnels. *Rock Mech Rock Eng* 51, pp. 2617–2637, DOI:[10.1007/s00603-018-1504-3](https://doi.org/10.1007/s00603-018-1504-3).