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PREFABRICATED GLASS FIBER REINFORCED CABLE DUCTS FOR BALLASTED HIGH SPEED RAILWAYS

(BALASTLI HIZLI TREN HATLARI İÇİN CAM LİFİ TAKVİYELİ KABLO KANALLARI)

Niyazi Özgür BEZGİN[1]

ABSTRACT

Prefabricated concrete cable ducts embody the transmission lines for the signaling and communication infrastructure of the high-speed railways. Reinforced concrete is widely used to fabricate cable ducts. A research conducted within a limited budget for the Ankara-Konya High Speed Railway project in Turkey showed that glass fiber reinforced mortar could reduce the weight of an ordinary reinforced concrete cable duct by more than 80%. This paper presents the experimental and the analytical work for the design, testing and fabrication of full-scale glass fiber reinforced cable duct samples and the experimental study to evaluate the possible effects of time related chemical corrosion on their mechanical performances.

Key words: High-speed railway, glass fibre, concrete, mortar, cable duct.

ÖZ

Önüretimli beton kablo kanalları yüksek hızlı tren hatlarının sinyalizasyon ve iletişim altyapısını içerirler. Bu kanallar sıklıkla betonarme olarak üretilirler. Ankara-Konya Yüksek Hızlı Tren projesi kapsamında çok sınırlı bir bütçe içerisinde yapılan bir çalışmada, cam lifi takviyeli harcın sıradan betonarme bir kanalın ağırlığını %80 oranında azaltabileceği tespit edilmiştir. Bu çalışma içerisinde tasarımın deneysel ve analitik kısmı, tam ölçekli bir kablo kanalının üretimi ve yükler altında tetkik edilmesi ile zamana bağlı çevresel aşınma etkilerinin araştırılmasına yönelik deneysel çalışma sunulacaktır.

Keywords: *Yüksek hızlı tren, cam lifi, beton, harç, kablo kanalı.*

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1. INTRODUCTION

High-speed railways have unique signalization and communication requirements compared to railways designed for normal speeds [1]. Unlike railways designed for normal speeds, electronic sensors and circuits collect and convey the operational data to the train operator's control panels. Therefore, the cross section of a high speed railway; whether it is constructed by ballasted track or slab track, must have an element that contains the necessary signaling and communication infrastructure.

Along a ballasted high-speed railway track in Turkey, these elements are typically reinforced concrete cable ducts embedded within the subgrade along the outer edges of catenary poles [2]. Lateral soil loads due to subgrade embedment and vertical live loads act on the embedded cable ducts. Laden maintenance crews typically cause the vertical live loads. In Turkey, concrete is currently a more economic construction material relative to structural composite plastics or cement infused hardening fabrics. Ordinarily, cable ducts are reinforced concrete elements with steel reinforcement bars or reinforcement meshes. However, the use of reinforcements also requires the use of concrete cover that adds to the total thickness of the cable duct resulting in an average total thickness of 5 cm. From a mechanical point of view, a large portion of the total thickness of reinforced concrete cable duct section is seldom due to structural requirements and but mainly due to concrete cover requirements for the reinforcement within. Based on this view, the study presented herein proposes that glass fibers can provide the necessary tensile strength to mortar cable ducts under the design loads [3]. Use of glass fibers can alleviate the use of reinforcement steel and hence the concrete cover, thereby reducing the total thickness and the weight of the cable duct.

2. FUNCTIONAL AND STRUCTURAL DESIGN ASPECTS

High-speed railway superstructure designers can position the cable ducts as close as 350 cm away from the outside rail of a track [4]. The major loads that act on the ducts at this distance are the lateral soil pressures based on the embedment depth of the duct and any surcharge as well as the vertical loads due to maintenance crews likely to walk along the side of tracks or on top of the ducts. The minor transient loads are due to train vibrations.

As a part of the Ankara – Konya High Speed Railway Project, the relevant specification required clear internal duct dimensions of 15 cm depth and 25 cm width [2]. The duct has a concrete cap and a 200 kgf/m design vertical live load of laden maintenance crew act on the duct. Duct embedment in sand with friction angle 30^{o} generates lateral soil pressures on the sidewalls of the ducts. Figure 1 shows the application of the vertical load and the resulting lateral load. The design lateral load is acting at mid-height rather than the lower third of the height due to the rigidity effects of the sidewall and the duct-base merge point. Based on the Rankine approach to the developed lateral earth pressure presented in Equation 1,200 kg/m vertical load on the subgrade by the maintenance crews generates an active 70 kgf/m lateral load on the side of the ducts. Figure 2 does not show the opposing base friction force and the lateral reaction developed on the opposing sidewall.

$$F_x = F_y * \frac{(1 - sin\varphi)}{(1 + sin\varphi)} = 200 * \frac{(1 - sin30)}{(1 + sin30)} \sim 70 \frac{kgf}{m} \qquad (1)$$

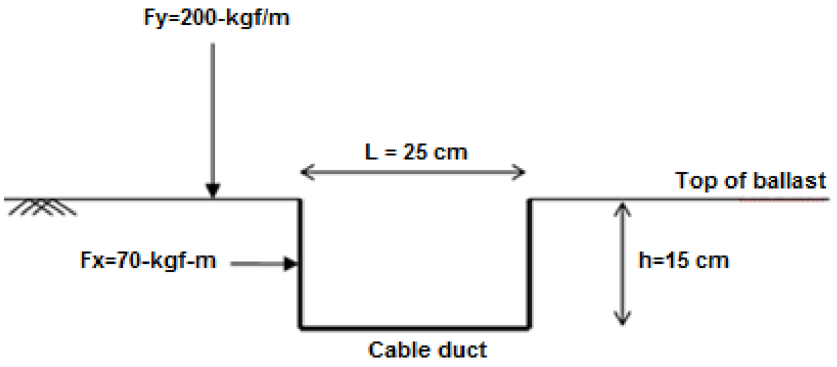

Figure 1. Sketch of the cable duct cross section under the action of lateral design load.

3. MATERIAL PROPERTIES

Alkali resistant, 13 mm long glass fibers reinforced the cable duct samples. Table 1 shows the design mixture quantities of the glass fiber reinforced mortar sample material. High early strength cement with strength of 52.5 MPa bonded the silica sand and fibers added at 2% ratio by weight of mixture. Selection of cement took into consideration equivalent alkalinity to be less than 0.6%. Table 2 and 3 show the qualities of the cement and the alkali resistant glass fibers respectively.

Table 1. Glass fiber reinforced mortar constituents.

Content	**Quantity (kg/m^3)**
Cement (CEM I – 52.5R)	921
Silica sand (AFS-43)	921
Alkali resistant glass fibers	45
Admixture (Glenium 51)	9
Water	327
Total	2.223

Table 2. CEM I-52.5R properties.

Chemical and physical properties	**Value and unit**
CaO	66.0 %
SiO_2	22.2 %
Al_2O_3	4.3 %
Fe_2O_3	0.2 %
Na_2O_3	0.155 %
K_2O	0.442 %
SO_3	3.6 %
MgO	1.35 %
Loss of Ignition	3.25 %
Insoluble Residue	0.14 %
Cl-	0.0103 %
Equivalent alkali	0.446 %
Initial Set	110 min
Specific gravity	3.15
Specific surface	4,600 cm^2/gr
2-day Strength	36.0 MPa
28-day Strength	59.0 MPa

Table 3. Alkali resistant glass fiber properties.

Property and unit	**Value**
Tensile strength of strand (MPa)	1.300
Modulus of elasticity (MPa)	73.000
Specific gravity	2.65
Ultimate strain	0.015
Filament diameter (μm)	15
Length (mm)	13
Zirconia content (% weight of glass)	19

Figure 2 and Figure 3 present the cumulative grain size distribution and the particle size histogram of the AFS-43 class non-reactive silica sand.

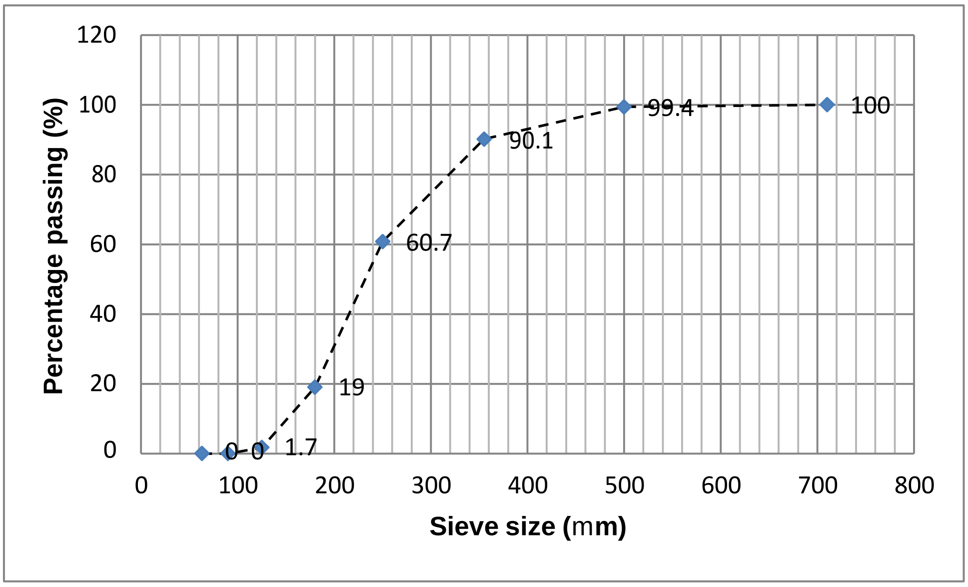

Figure 2. Silica sand gradation.

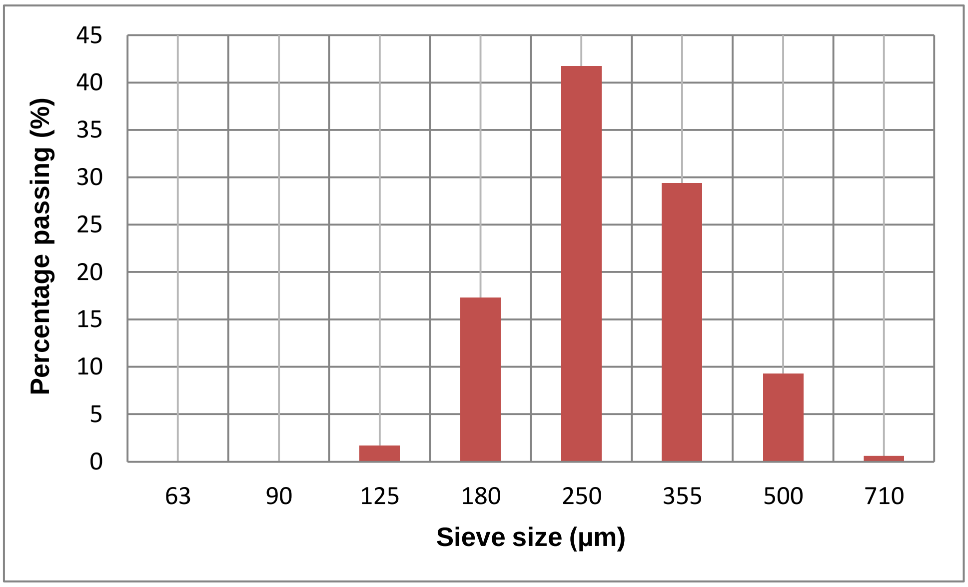

Figure 3. Histogram of silica sand particle size distribution.

Figure 4 shows 4-point bending tests on 28-day-old, 50 cm x 10 cm x 1.2 cm samples that revealed the bending behavior of the design material.

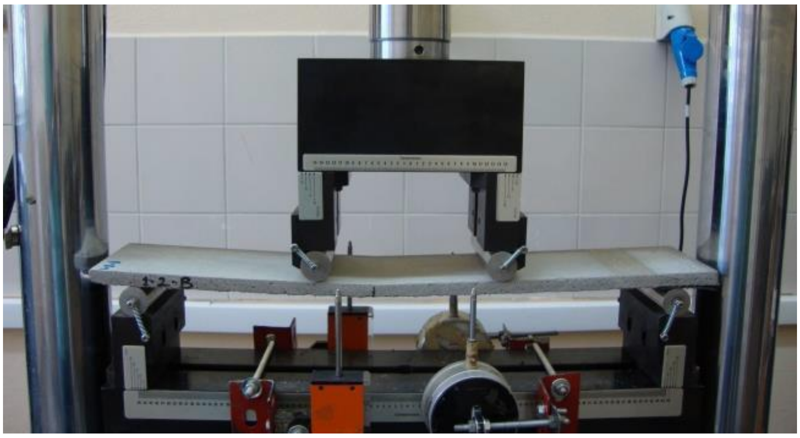

Figure 4. Four-point bending tests of thin plate samples.

Figure 5 shows the stress - displacement behavior of a set of 28-day-old samples (set 1-1 A, B, C and D) placed under plastic covers and cured at 21^{o}C for three days. The figure also shows the material's early elastic strength limit and its early bending strength limit at 10.5 MPa and 12.1 MPa respectively.

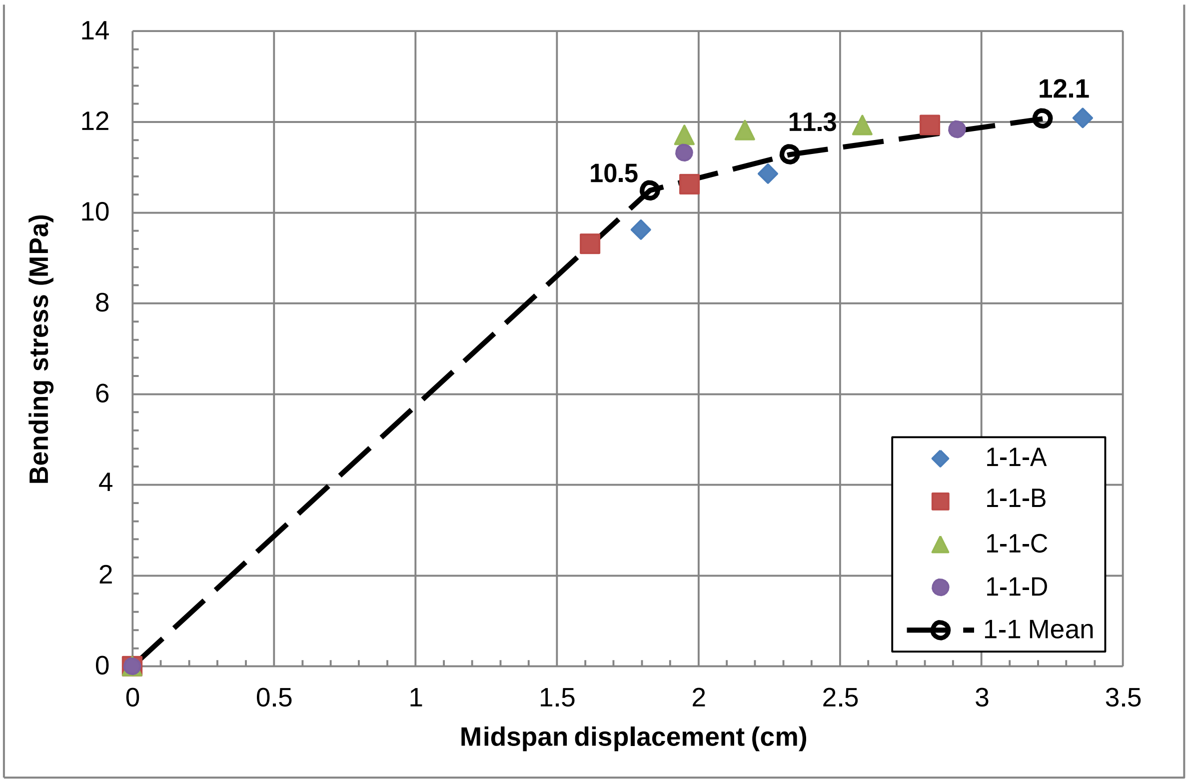

Figure 5. Bending stress displacement curve of sample group 1-1.

Figure 6 presents the cylinder compressive strength values of 2-sets of samples with 3 samples each tested respectively at 3 days, 7 days and 28 days.

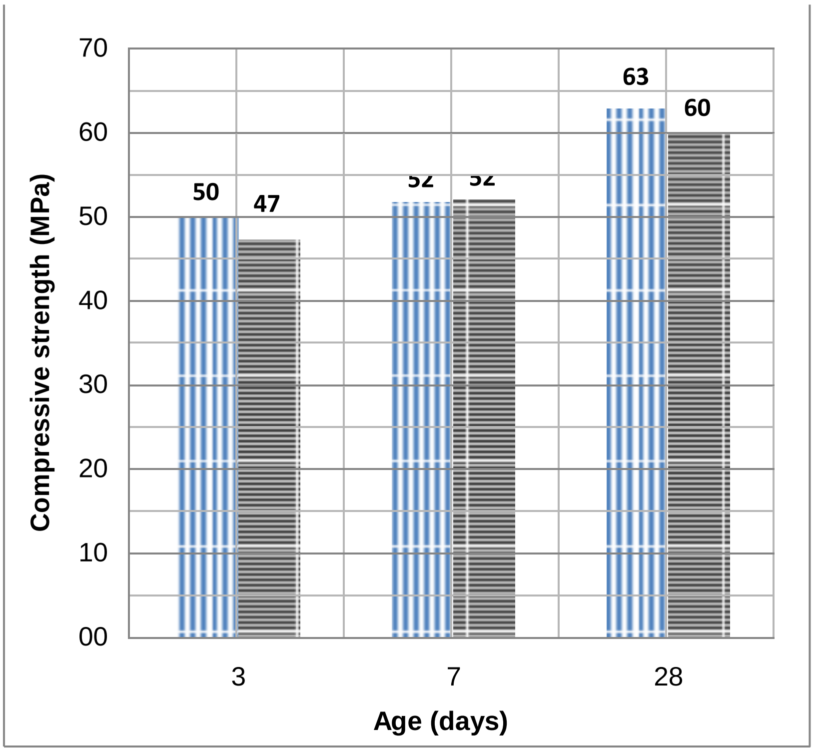

Figure 6. Cylinder compressive strength values of 2-sets of glass fibre reinforced mortar samples.

4. EFFECTS OF CORROSION ON MECHANICAL PERFORMANCE

Cable ducts serve within an environment constantly exposed to outdoor weather conditions. Since the cable ducts thickness is thin, any loss in the cross section or the fiber bond strength due to freeze-thaw cycles and corrosion can be highly detrimental to the bending capacity of the duct [3, 5, 6, 7]. To this end, freeze-thaw resistance and the resistance of the cable ducts to chemical attacks are important. Freeze-thaw resistance of glass fiber reinforced cable ducts is well documented in many studies [6, 7]. Due to the low porosity of the mortar along with the beneficial effect of injection molding that further reduce porosity, permeability tests conducted as a part of this study yielded the result that 5 mm thick fiber reinforced mortar plate samples could withstand 9.8 kPa static water pressure for 2 weeks. During corrosion tests that lasted three weeks, three pieces of 35-day-old 100 cm long cable ducts and duct caps divided into 10 cm long specimens remained submerged in acidic and basic environments as shown in Figure 4.

Corrosive environments achieved by mixing 250 cl of hydrochloric acid with 45 liters of tap water, 500 cl of hydrochloric acid with 40 liters of tap water and 1.8 kg of sodium hydroxide with 36 liters of tap water resulted in pH values of 2.6; 2.3 and 14 respectively. Figure 7 shows the samples exposed to corroding agents for 3 weeks. Beginning from left, the figure shows the first box of samples exposed to a pH value of 2.6; the third box of samples exposed to a pH value of 2.3 and the fourth box of samples exposed to a pH value of 14. The second box contained samples with polypropylene fibers the results of which are excluded from this study.

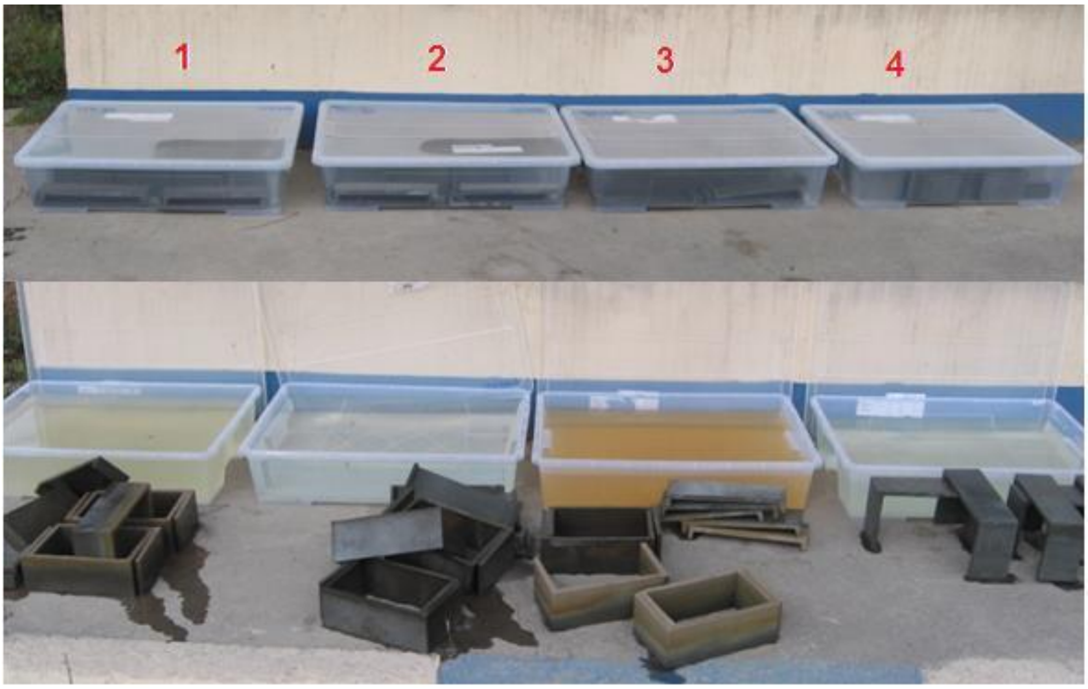

Figure 7. Cable duct samples submerged in corrosive environments.

100 cm long ducts sawn to yield 10 smaller samples that were10 cm long each. Five samples remained submerged in each solution and five samples provided the control set unexposed to corrosion. However some of the samples cracked during preparation. The samples that cracked lost a part of their bending capacity and thus excluded from the bending tests that commenced. Figure 8 shows the testing of the intact samples placed sideways. The tests determined the failure strength of the samples. Figure 9 shows the aged bending strength values of the glass fiber reinforced material, estimated from the cross sectional properties and the value of the applied load “P” at failure.

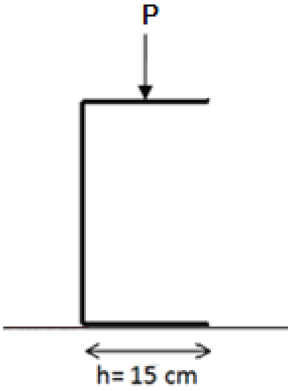

Figure 8. Side elevation view of a 10 cm long cable duct sample.

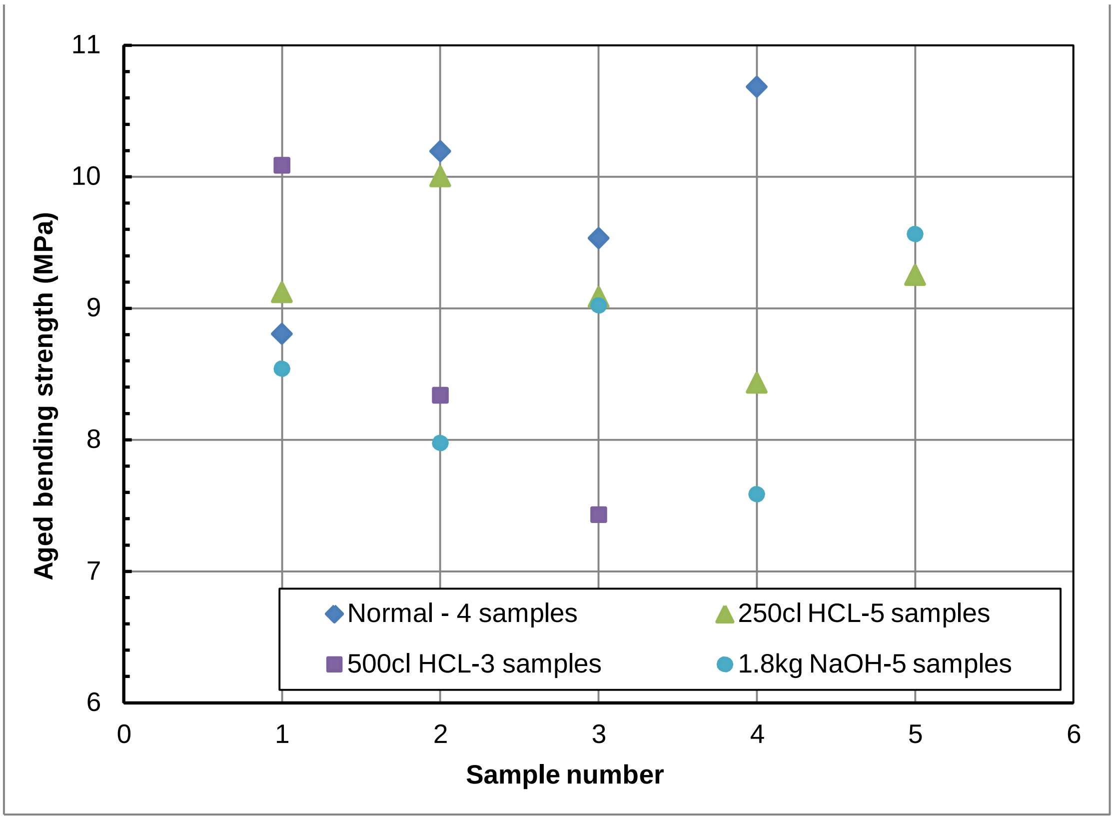

Figure 9. Aged bending strength values of the test material.

Figure 10 shows the arithmetic mean of the aged strength values obtained from the samples.

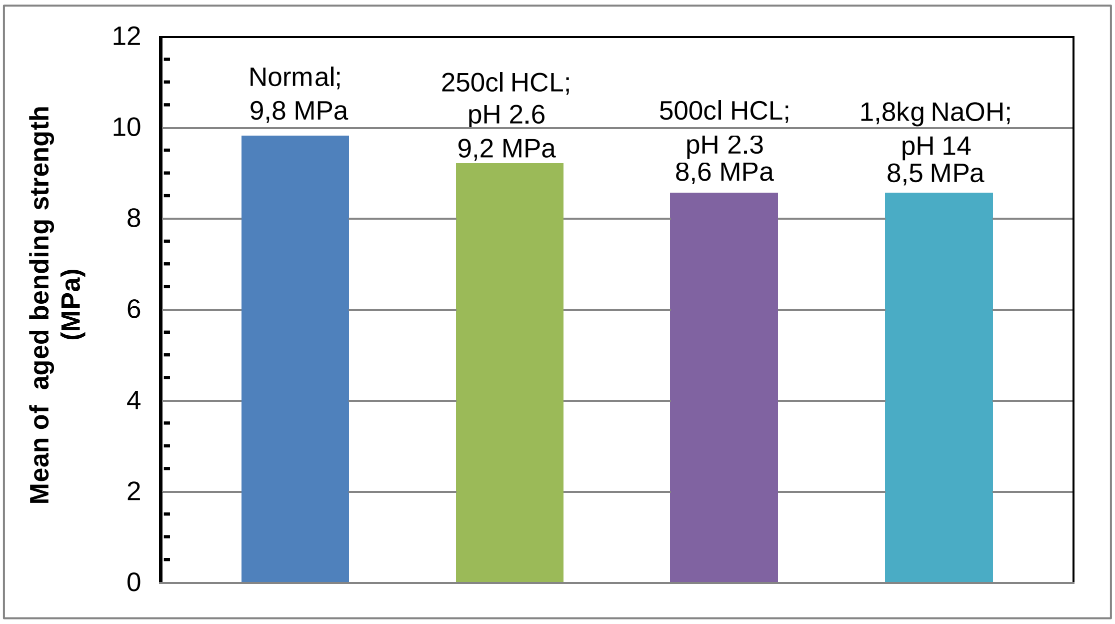

Figure 10. Mean-aged bending strength values for each exposure.

Exposure of glass fiber reinforced duct samples to corrosive environments with extreme pH values allowed the visualization of the effects of worst-case exposure scenarios. The discovery was that the bending strength of the aged samples reduced upto 15% by the action of corrosion as shown in Table 4.

Table 4. Reduction in the fiber-reinforced cable duct bending strength with exposure to corrosive agents.

Submerged corrosive environment	**Average bending strength reduction with respect to "the normal set"**
None (the normal set)	Reference
250cl HCL, pH 2.6	%7
500cl HCL, pH 2.3	%13
1.8kg NaOH, pH 14	%14

The 9.8 MPa mean ultimate strength of the aged sample set; unexposed to corrosive agents (the "normal" set), was lower than its early ultimate strength value of 12.1 MPa shown in Figure 3 earlier. This is an expected behavior since it is determined that, the glass fiber reinforced material loses strength and ductility with time [8, 9]. The elastic strength limit is determined to increase with time and converge to the decreasing ultimate strength value.

5. DESIGN, TESTING ANALYSIS AND FABRICATION OF THE CABLE DUCT

Following the determination of the design load and the mechanical properties of the material, the duct design and analysis commenced. The duct design enabled elastic behavior under service loads and ductile failure under ultimate loads. The limited number of samples used for this study was not large enough to define statistically the characteristic bending strength value. Therefore, the design used the mean of the available bending strength results.

Supplemented by the findings of the previous section, the possible effects of extreme contamination was judged to reduce the aged bending strength of the glass fiber reinforced material section; which was determined to be on average 9.8 MPa, by 15%. The design guidelines [8, 9] frequently use and specify the material factors based on un-aged material properties, which for the case presented herein was 12.1 MPa.

Practical Design Guide for Design with GFRC by GRCA [8] addresses the load factor as 1.4 for dead load and 1.6 for live loads. Based on the Recommended Practice for Design with GFRC by PCI [9], the recommendation for the dead load factor is 1.4 and the live load factor is 1.7. Both guides recommend the material factor for un-aged materials as 0.25. Based on the findings about corrosion, an additional factor of 0,85 is accounted for the 15% bending strength loss.

5.1 Design

Figure 1 shows the design loading case for the cable duct. The design considered the bending effect of the lateral load applied to the sidewall at a height of 7.5 cm from the base of the wall. With the known elastic and ultimate stress levels, the design outcome was the base and sidewall thickness *(t)* of the duct. The lateral service load (F_s) determined earlier was 70 kgf/m.

For the design of the cable duct, the design ultimate load *(F_{ud})*:

$$F_{ud} = 1.7 * F_s = 1.7 * 70\frac{kgf}{m} = 119\frac{kgf}{m} \quad (2)$$

The design moment *(M_d)*:

$$M_d = F_d * 7.5\,cm = 893\,kgf - cm \quad (3)$$

The design material ultimate strength *(f_{ud})*:

$$F_{ud} = 0.25 * 0.85 * f_u = 0.3 * 12MPa = 2.5MPa = 25.5\frac{kgf}{cm^2} \quad (4)$$

The material elastic strength *(f_e)*:

$$f_e = 10MPa = 102\frac{kgf}{cm^2} \quad (5)$$

Elastic section modulus *(S)* relates to the length *(l)* and the sidewall thickness *(t)* of the duct:

$$S = {}^{1.t^2}\!/_{6} \quad (6)$$

Plastic section modulus *(Z)* relates to the length *(l)* and the sidewall thickness *(t)* of the duct:

$$S = {}^{1.t^2}\!/_{4} \quad (7)$$

Design thickness for 100 cm long cable duct:

$$M_d = f_{ud} * Z \quad (8)$$

$$893 = 25.5 * 100 * \frac{t^2}{4} \rightarrow t = 1.18cm = 1.2cm$$

Stress at service load relates to the generated moment *(M_s)* under the service loads:

$$M_d = f_s * S \quad (9)$$

$$M_s = 70kgf * 7.5cm = f_s * 100 * \frac{1.2^2}{6} \rightarrow f_s = 21\frac{kgf}{cm^2} = 2MPa < f_e = 10MPa$$

Figure 11 shows the cross section of the cable duct with a design base thickness of 1.2 cm and an average sidewall thickness of 1.2 cm.

1-meter long cable duct and duct cap consumed approximately 0.011 m^3 of glass fibre reinforced material. The density of the glass fiber reinforced material was 2.223 kg/m^3. The weight of 1-meter long cable duct and duct cap was 25 kgf. This was a significant saving in weight, compared to the weight of an ordinary 5 cm thick reinforced concrete cable duct, which was 150 kgf.

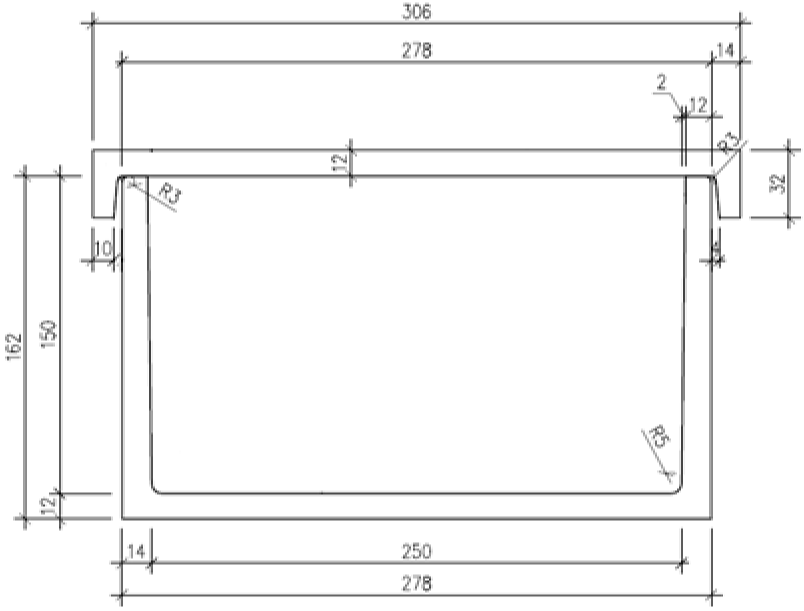

Figure 11. Cross sectional dimensions of the cable duct and its cap in millimeters.

5.2 Analysis

The initial design of the duct involved the application of the lateral soil pressure due to the vertical load as shown in Figure 1. The design of the cable duct considered the maximum bending stress level that occurred along the sidewalls of the duct under the effect of lateral soil pressure. Another design assessment included the application of the vertical design load acting directly on the duct through the duct cap. The assessment considered the effect caused by a maintenance worker walking along the top of an improperly supported duct. Continuous soil support should exist below the duct under sound design guidelines and installation procedures.

However, the behavior assessment of the duct under the design vertical load considered an adverse soil support condition that considered a case without full soil support. A common finite element linear-elastic analysis program analyzed the behavior of the duct as a structural element, simply supported at its ends under the application of 200 kgf per meter vertical design load applied at the middle of the 1-meter span distributed along a length of 15 cm and a lateral design load of 70 kgf per meter distributed at mid-height along the side of the both walls. The analysis disregarded the beneficial effects of the cable-duct-cap for lateral support on the sidewalls due to friction. Figure 12 shows the loaded design model generated by 8-node linear elastic solid elements and the bending stresses along the length of the cable duct under the simultaneous action of the design vertical and lateral loads.

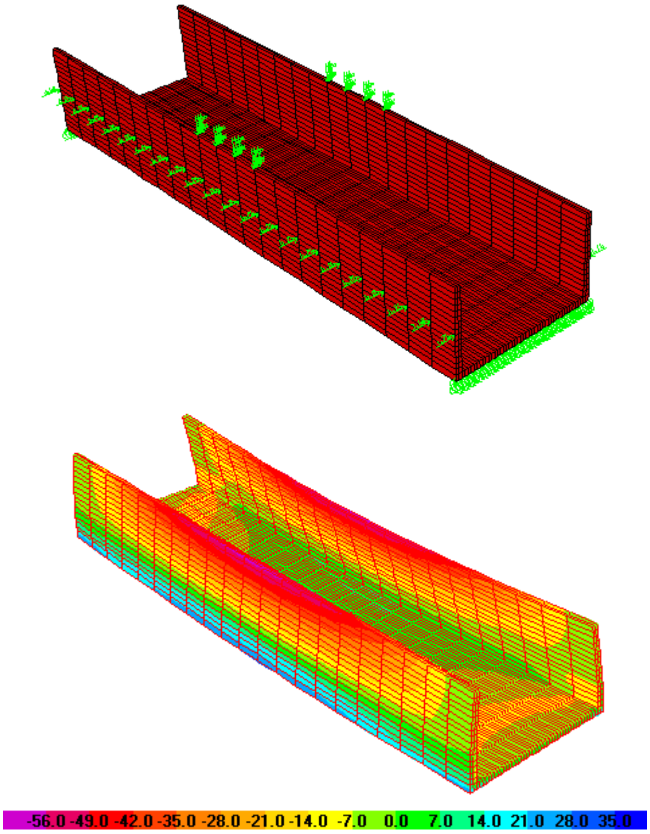

Figure 12. Finite element model of the loaded cable duct and bending stress distribution.

The analysis yielded bending stresses with the highest value of 56 kg/cm^2 (5.5 MPa) in compression and the highest value of 35 kg/cm^2 (3.4 MPa) in tension. The analysis did not indicate local buckling along the compressive edges throughout the numerical evaluation.

5.3 Testing

Testing sequence required production of an initial set of count-10 sets of sample cable ducts. The design dimensions of the cable ducts are 100 cm length, 1.2 cm average thickness, 16.2 cm external depth and 28 cm width. The cap thickness is 1.2 cm and the cap external width is 30 cm.

Due to the unavailability of more elaborate high precision automated mechanical testing possibilities at the time of the study, manually placed precise concrete counterweight blocks loaded the test samples. Figure 13 shows count-four blocks weighing 20 kgf each, placed at the tip of the side of the cable duct. The four tested samples responded elastically to the loading effect of the counterweights that weighed 80 kgf.

Figure 13. 100cm long cable duct laterally loaded with 80 kgf.

The duct is also loaded as a simply supported beam with 225 kgf applied at the mid-span as shown in the right hand side of Figure 10. The simply supported condition meant to disregard the soil support underneath that a buried duct would normally have. The weight of the lower three blocks applied was 30 kgf each, the middle three was 25 kgf each and the top three was 20 kgf each. The 4-samples tested under vertical load did not fail. The tests did not reveal any signs of local buckling along the sidewall edges subjected to compression.

5.4 Fabrication

An important benefit of the thin plate structure of the glass fiber reinforced cable duct is the possibility to cast surfaces in three dimensions [10, 11]. Figure 14 shows glass fibre reinforced duct samples produced by white-cement. A tongue and groove detail allowed a simple but an effective inter-alignment mechanism between the consecutive cable ducts. However, ordinary free-flow casting method employed in the production of the initial samples could not achieve the proposed detail unless the use of time-consuming special attachment installation within the mould. The out-of-plane character of the detail required the use of injection moulding typically employed in the plastic industry.

Figure 14. Tongue and groove detail of the cable duct**.**

A patented injection molding sequence enabled the production of the thin ducts with the proposed connection detail. The sequence did not require any special detailed mould attachments and the simple two-piece mould received mortar injection at a 0.5 bar pressure.

6. CONCLUSIONS

The study showed that glass fiber reinforced mortar had a potential to replace the normal strength reinforced concrete 5 cm thick cable ducts selected for the Ankara – Konya High Speed Railway shown in Figure 15.

Figure 15. Reinforced concrete cable duct (Cap not shown).

The material cost of the 1.2 cm thick glass fiber reinforced cable ducts was equal to the 5 cm thick reinforced C30 grade concrete cable duct. Moreover, the 25 kgf/m weight of the proposed duct was 17% of the weight of the reinforced concrete ducts that weighed 150 kgf/m. Figure 16 shows the dimensional comparison of glass fiber reinforced cable duct and ordinary steel reinforced concrete cable duct cross sections.

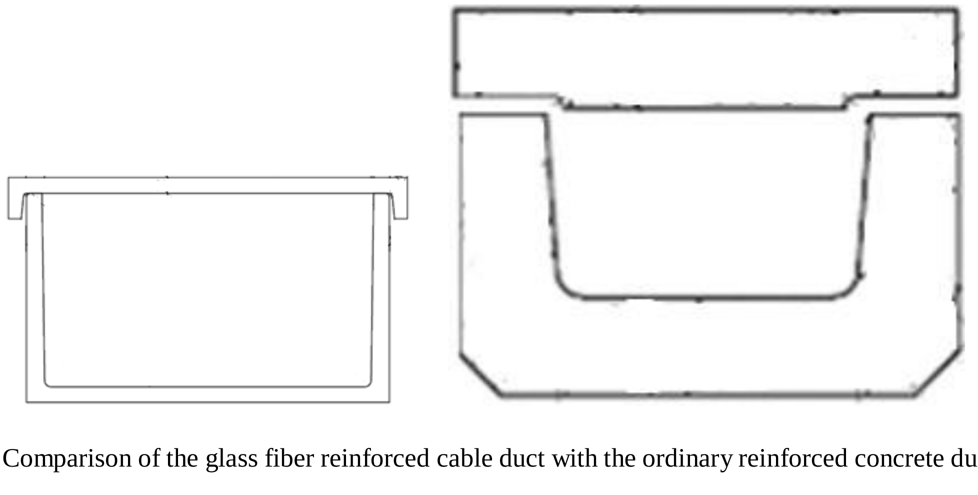

Figure 16. Comparison of the glass fiber reinforced cable duct with the ordinary reinforced concrete duct.

1. The presented study yielded the following conclusions and recommendations:
2. Glass fibre reinforced mortar with 2% fiber content by mixture weight can provide 9 MPa aged elastic design strength.

3. The available elastic design strength of glass fibre reinforced mortar can negate the need for corrodible steel reinforcements in certain structural designs such as the design of thin walled cable ducts used along high-speed railway superstructures.
4. Lack of corrodible steel reinforcements negate the need for cover that has an insignificant structural contribution but a significant deadweight contribution.
5. The presented case involved the structural design of a glass fibre reinforced cable duct exposed to lateral soil loads of 70 kgf/m and 200 kgf/m live loads by laden maintenance workers.
6. The estimated load levels acting on the structure, generated stress levels ranging from compressive 6 MPa to tensile 4 MPa that were within the admissible elastic stress range of glass fibre reinforced plate elements with an average thickness of 1.2 cm.
7. The study investigated the effects of corrosive environments on the structural qualities of the designed cable duct within extreme acidic and basic conditions with pH values varying from pH: 2.3 to pH: 14. The corrosion tests revealed a 15% reduction of bending capacity.
8. The proposed method of glass fibre reinforced mortar cable duct production with an average thickness of 1.2 cm reduced the self-weight of the normal steel reinforced concrete cable duct with an average thickness of 5 cm by 83%.

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ÖZGEÇMİŞ / CV

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Yard. Doç. Dr. N. Özgür Bezgin, Rutgers, the State University of New Jersey'de derin temellerin yan yükler altında yapı-zemin etkileşimi üzerine yaptığı çalışmalar ile 2005 senesinde Doktora derecesini aldı. Mezuniyetinin ardından özel sektörde zemin, yapı ve ulaştırma alanlarında çalışmalar yaptı. 2012'de ulaştırma mühendisliği yapıları alanında çalışmalar yapmak üzere İstanbul Üniversitesi, İnşaat Mühendisliği Bölümü'ne katıldı.