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Evaluation of the effect of using fiber reinforcement in tunnel linings for metro projects

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Abstract

Metro (subway) is an advanced public transport infrastructure system in urban areas with high capacity. The traffic operation of a metro is not affected by other vehicle traffic thanks to underground tunnels. With these benefits metro lines are preferred to solve the traffic problem in urbanized cities such as Istanbul, which is the focus of this study. Metro projects require huge amounts of budgets to be built. Putting these projects into service in targeted time is of great importance. The objective of this study is to minimize total metro construction project time by utilizing fiber reinforcement in tunnel linings. In this research, using fiber reinforcement to construct primary (initial) tunnel linings and secondary (final) tunnel linings of the metro projects are analyzed in terms of project duration. After comparison of two railway tunnel projects, evaluations and observations of a completed metro project revealed that using fiber reinforcement for either the primary lining or the final lining of tunnels reduces construction time of metro station tunnels by 25%. In addition, using fiber reinforcement to construct both the final lining and the primary lining of tunnels reduces construction time of the metro station tunnels and the whole metro project by 47% and 22%, respectively. The results of this study can be useful for completing challenging metro projects and putting it into service within the targeted time.

Keywords: Metro; Tunnel; Tunnel linings; Shotcrete; Fiber Reinforced Shotcrete; Tunnel Boring Machines

1 Introduction

Successfully managing a construction process requires being familiar with the specific difficulties and characteristics of the project. Underground metro construction has specific conditions and complexities unlike other construction projects. When compared to other construction projects, the distinct difference of metro projects comes from the integrated internal and external complexities. External complexities result from the location of the site where metro construction projects will be realized. This exceptional feature increases the complexity of planning and management in such projects more than other structures (Khosravi & Kähkönen, 2015).

Han et al. (2009) indicated that project managers should consider various social and political factors in addition to time, cost, and quality, to manage a project successfully. When potential delay causes are identified early, the delayed activities can become a part of the as-built critical path. Often, more serious delay factors tend to be found on the updated critical path of the critical sections. The same study concluded that project managers should find proper measures to address delays and conduct proactive actions by utilizing the multilateral approaches by identifying delay factors in the critical sections, both in macro- and micro-levels, could lead to successful project management of mega-scale projects. The construction site schedule control and the key of construction site schedule control were investigated by various researchers in mega metro projects in China (Gao, 2010; Li & Bao, 2007; Yuan, 2015; Zhan & Liu, 2003).

Globally, the works in any metro projects are divided into two main parts as construction works and electromechanical works. The duration of the construction works is very critical to put the metro into service within the planned time because the electromechanical works cannot

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start before the completion of tunnel construction works. In fact, a metro tunnel project consists of two main categories of tunnels; the tunnels bored by tunnel boring machines (TBMs) and not bored by TBMs. Main line tunnels which are built by TBMs and other tunnels such as platform (metro station), switch, stairway tunnels which have different dimensions than the section of mainline tunnel are not able to be bored by TBMs because these tunnels have different cross sections than the TBM diameter or the mainline tunnels. These tunnels are constructed by classic tunnel boring method which is named as New Austrian Tunneling Method (NATM). In this method, a tunnel is bored, and then shotcrete is applied to the bored surface; afterwards wire mesh reinforcement is placed, and then another shotcrete is applied to cover the wire mesh reinforcement. This process is known as primary tunnel lining. After completing this initial process, a material to provide water insulation is placed before the placement of the main reinforcement; to finalize the tunnel construction, concrete is poured in moving formworks to cover the main reinforcement. This process is known as secondary (final) tunnel lining.

Primary tunnel linings can be built by either shotcrete sprayed on wire mesh reinforcement or by spraying fiber reinforced shotcrete. Secondary tunnel linings can be built by spraying fiber reinforced shotcrete or by pouring concrete in moving formworks after binding the reinforcement of secondary (final) tunnel lining or by pouring fiber added concrete in moving formworks. The difference between fiber reinforced shotcrete and fiber added concrete is that at fiber reinforced shotcrete fiber is mixed in shotcrete and applied by spraying and no formwork is used. At fiber added concrete, fiber is mixed with concrete and then poured in formworks to build secondary lining.

Sometimes a metro project cannot be completed within the targeted period due to the delays either in the construction of metro stations or in the constructions of metro tunnels. In fact, even though constructions of some metro stations were completed, the whole metro line could not be put into service altogether due to the delay of constructions of metro station tunnels (Namli, 2018).

Nowadays, tunnels can be constructed in shorter times due to extensive utilization of TBMs. Depending on geological conditions, approximately only 1 m of a tunnel in average can be bored per day with classic tunnel boring methods (NATM), while TBMs can bore approximately 10 m per day in average. Namli et al. (2013) developed an initial progress estimation model for geological formations in Istanbul region to estimate the performance of TBMs. By virtue of this model, it is possible to estimate how long it would take to construct a tunnel by using TBMs depending on the type of the geological formations (Namli & Bilgin, 2017).

In this context, it is obvious that planning the construction technique of metro stations and tunnels on the metro line before the project begins is extremely important. According to a World Bank report (Alan, 2002), the construction time of rail system metro projects across the world takes at least 5 years excluding the expropriation period. Metro projects are generally carried out on financial loans: the completion of such projects on time and putting the metro line into service to generate revenue helps facilitate repayment of the bank loans. Repayment of existing loans also enables administrations to finance additional similar metro projects. Therefore, conducting studies on shortening the completion duration of such projects is of great importance.

2 Research need

Compared to the application of fiber reinforced shotcrete, the application of wire mesh reinforcement at tunnel linings is not only difficult but also time-consuming and requires labor-intensive workmanship. One of the main disadvantages of wire mesh reinforcement is the inability to place the wire mesh with proper concrete cover allowance and the use of excessive amounts of shotcrete in wire mesh shotcrete applications. Compared to the shotcrete reinforced with wire meshes, fiber reinforced shotcrete has less material consumption, because the configuration of excavation is followed better. Fiber increases the homogeneity, tensile and shearing strength of the shotcrete. Fiber reinforced shotcrete is more resistant to abrasion, corrosion and impacts. Significant increases in load-carrying capacity, tensile, fatigue and impact resistance after cracking can be achieved with various types of fibers added to shotcrete. Due to the difficulties in the application of wire mesh and the advantages of fiber reinforcements, different type of fibers such as synthetic, polypropylene, glass, polymer, amorphous, polyamide and steel fibers have started to be used as an alternative in shotcrete applications. There have been a lot of researches about mechanical properties of fiber reinforcement in literature. For instance, Chiaia et al. (2009) studied the presence of steel fibers into cast-in situ steel fiber reinforced concrete tunnel linings. It was found that steel fibers provided not only relevant structural advantages both during serviceability and ultimate limit states, but also reduced crack width even in the presence of few steel bars, and concluded that a faster advancement in construction and a reduction of global costs can be achieved. Morgan and Mowat (1984) reported that steel fiber reinforcement has been found to be equivalent or even superior to traditional welded wire mesh reinforcement. Morgan et al. (1990) reported a comparison of load vs. deflection test results for previously tested steel fiber reinforced shotcrete in large unrestrained test panels. It was indicated that the polypropylene fiber reinforced shotcrete with 6 kg/m^3 of 38 mm long polypropylene fiber reinforcement had a similar performance to the steel fiber reinforced shotcrete with 59 kg/m^3 of hooked-end steel fiber and the addition of high-volume concentrations of polypropylene fiber reinforced shotcrete up to 6 kg/m^3 of 38 mm long polypropylene fiber can provide a viable alternative to traditional mesh or steel fiber reinforcement of wet-mix shotcrete for many applications. To compare mechanical properties of fiber reinforced shotcrete and shotcrete reinforced with wire mesh, flexural tests on panels reinforced with wire mesh (11 kg/m^3 of steel) and on panels reinforced with 25, 30, and 35 kg/m^3 of hooked-ends steel fibers were carried out by Barros. Barros (1998) reported that after cracking the load carrying capacity increases with the fiber content. The peak load of the series of panels reinforced with 35 kg/m^3 of fibers was observed 27% higher than the peak load of the panels reinforced with wire mesh (Barros, 1998). The peak load of the panels reinforced with 25 kg/m^3 of fibers was observed quite near that of the panels reinforced with wire mesh (Barros, 1998). Barros stated that more significant improvements were observed in the energy absorption capacity. It was observed that for the panels reinforced with 35 kg/m^3 of fibers the energy absorption capacity was 116% higher than the one obtained for the panels reinforced with wire mesh (Barros, 1998).

Mechanical property of lining with fiber reinforced shotcrete depends on the kind of fiber and mixing ratio. Liu et al. (2017) reported that when the polypropylene fiber length increased from 3 mm to 29 mm, the compressive and splitting tensile strength was reduced. Liu et al. attributed this to the fact that longer fibers have more cluster problems in the concrete matrix than shorter fibers. Khooshechin and Tanzadeh (2018) studied glass fiber reinforced shotcrete specimens and found the increases up to 6.58%, 28.81%, and 43.38% in compressive, splitting tensile and bending strength, respectively. Baricevic et al. (2018) reported that the addition of recycled tire polymer fibers did not have a considerable influence on the mechanical properties of shotcrete. Yang et al. (2017) compared the effects of steel fibers and amorphous metallic fibers on mechanical properties and rebound rate of shotcrete. The results show that amorphous metallic fibers have higher flexural strength and rebound rate than steel fibers, but have lower toughness capacity. Jeon et al. (2016) reported that when the polyamide fiber ratio increased from 0.5% to 1.5%, compressive, flexural strength and toughness capacity of polyamide fiber reinforced shotcretes increased linearly. Yan et al. (2018) reported that the steel fibers can significantly improve splitting tensile, flexural and shear capacity of the shotcrete by 77.42%, 72.73%, and 98.31%, respectively. Banthia et al. (1994) studied geometric shapes of steel fibers. The investigation of the effects of steel fibers with different geometric shapes namely flat, two hooked-end and deformed on the toughness showed that two hooked-end fibers are more effective in increasing the toughness capacity compared to flat and deformed fibers. The effects of different types of two hooked-end steel, polyamide and synthetic fibers that are widely used in construction applications on the fresh and hardened concrete properties of shotcrete were investigated by Guler et al. (2021). Guler et al. reported that the steel fiber reinforced shotcrete (STFRS) specimens exhibited more ductile behaviour than the polyamide fiber reinforced shotcrete and the synthetic fiber reinforced shotcrete specimens due to the two hooked ends of the fibers being stripped from the concrete matrix. Also, Guler et al. reported that the contribution of all fibers to the increase in splitting tensile and flexural strength was more significant than the increase in compressive strength of shotcrete. The greatest increase in the splitting tensile and flexural strength was obtained as 39.01% and 45.89% for the STFRS specimens, respectively. Guler et al. (2021) reported that significant increases (up to 10%) in the compressive strength of STFRS specimens only occurred at a volumetric ratio of 1%. And the greatest increase in the compressive strength was obtained as 17.22% for the STFRS specimens. They reported that when the fiber volume ratio was increased from 0.25% to 1%, the slump values of all the fiber reinforced shotcrete mixes reduced drastically and the workability of concrete was most negatively affected by the polyamide fibers at the same volumetric ratios due to their high absorption of water.

As mentioned above, there are a lot of researches about the mechanical properties of fiber reinforcement (Casanova et al., 1997; Chiaia et al., 2005; Falkner & Henke, 2005; Fantilli et al., 1999; Fun & Hsieh, 2011; Hillerborg et al., 1976; Hillerborg, 1980, 1985; Hu & Day, 2000; Morgan et al., 1995; Rilem, 1985, 2002, 2003). The durability of shotcrete was also investigated by many researchers (Galan et al., 2019; Hauki & Beck, 2018). Therefore, the mechanical properties of fiber reinforcement and the durability of shotcrete are not in the scope of this study.

The construction time of metro tunnels by utilizing TBMs can be predicted depending on the soil type (Namli & Bilgin, 2017). However, in a metro project, there are such tunnels as platform tunnels, ventilation tunnels, stairway tunnels and access tunnels that need to be bored without using any TBM because of the varying cross sections of these tunnels. New Austrian tunneling method is generally utilized to construct these tunnels. In this method, a tunnel is bored, and then shotcrete is applied to the bored surface; afterwards wire mesh reinforcement is placed, and then another shotcrete is applied to cover the wire mesh reinforcement. This process is known as primary tunnel lining. After completing this initial process, a material to provide water insulation is placed before the placement of the main reinforcement; to finalize the tunnel construction, concrete is poured in moving formworks to cover the main reinforcement. This process is known as secondary (final) tunnel lining. In this paper, these two consecutive processes together will be denoted as D1. It is the primary and secondary tunnel lining construction time that controls how fast a metro tunnel project will be complete on time; in this sense, the number of TBMs alone utilized in the whole project becomes less important.

The objective of this study is to minimize the total metro construction project time by utilizing fiber reinforcement in tunnel linings. The research component of this study is the investigation of the required tunnel lining construction method and the adequate number of tunnel boring machines (TBMs) to be able to complete a metro project within the targeted time. The target completion time of the metro project is 42 months and the total budget is 563-million-euro. One of the main restrictions is the number of TBMs which must be at least 4 according to the current contract. The other constraint is the length of tunnels that must be constructed by NATM which cannot be dug by TBMs due to various cross sections. Another constrain is that the start of tunnel electromechanical works requires the completion of the construction of all tunnels. In this context, this study analyses the reduction in construction time, which could be achieved by the use of fiber reinforcement instead of wire mesh or main reinforcements in the tunnel linings.

3 Methodology

In order to analyze the effects of using fiber reinforcement in the tunnel linings on the construction completion time of metro projects, there are six different scenarios to be considered in this study summarized at Table 1. The first one (D1) is the current common construction method and the others are alternative methods investigated.

The duration steps of tunnel construction in terms of D1 through D6 are recorded at the jobsites during the constructions of two different railway projects: (1) Üsküdar-Ümraniye-Çekmeköy Metro (UUCM) Project in Istanbul and (2) Awash-Kombolcha-Haragebeya High-Speed Rail Line (AKHRL) Project in Ethiopia. The cross section of tunnels of AKHRL project is similar to cross section of tunnels of the UUC Metro project. However, reinforced shotcrete was used to build the primary tunnel linings at AKHRL Project, while there was no reinforced shotcrete application in UUCM tunnels. When the jobsite recordings are scrutinized in detail, it is observed that construction duration of tunnel linings are similar between the two projects. Hence, construction duration of the primary linings with fiber-reinforced shotcrete in AKHRL project is taken into consideration, and the effect of the case of using reinforced shotcrete in UUCM tunnels is analyzed for both the completing duration of metro stations and the completing duration of the whole metro project.

The following methodology, which is illustrated at Fig. 1, is pursued in this study. Firstly, the effect of using fiber-reinforced shotcrete for primary and secondary tunnel linings is analyzed. Secondly, the effect of using alternative tunnel lining construction methods on the completion time of the metro station tunnels are evaluated and compared with each other. Then, the effect of using alternative tunnel lining construction methods on completion time of the whole project is investigated. Finally, the combination of utilization of fiber reinforced shotcrete to build tunnel linings and the required number of TBMs is analyzed to minimize the construction time of a metro project.

The data collection process was done by each responsible person on site with a stopwatch for NATM tunnels. All recorded data were collected at jobsite progress reports daily. In addition, the information of TBM progresses was captured from the tunneling machine and recorded daily.

4 Results

In this part of the paper, effects of various utilization of fiber reinforcement for tunnel lining construction are presented.

4.1 Effects of changing the construction method of the metro tunnel lining

Üsküdar-Ümraniye-Çekmeköy Metro Line is a mass transportation rail system. The length of the main tunnels between Üsküdar and Çekmeköy stations is approximately 17 km and there is also an approximately 2.8 km long access tunnel to depot area. The total length of this two-tube mainline tunnel is approximately 20 km. There are 16 stations with two-tube bored and cut-and-cover tunnels, depot area, maintenance area and buildings. The 17 km long mainline begins from Üsküdar station at Üsküdar Square and reaches up to Çekmeköy Station. In addition, a 2.8 km long tunnel access line diverging from the mainline in Dudullu locality reaches to Depot Area (Fig. 2). The total budget for the construction and electromechanical works of the metro line, which was contracted out by

Table 1
Tunnel lining building methods.

Method	Tunnel lining building method explanation
D1	The method of constructing the primary tunnel lining with shotcrete on the wire mesh reinforcement and constructing the secondary (final) tunnel lining by pouring concrete in moving formworks after binding the reinforcement of secondary (final) tunnel lining.
D2	The method of constructing the primary tunnel lining with conventional shotcrete on the wire mesh reinforcement and the secondary (final) tunnel lining with fiber-reinforced shotcrete.
D3	The method of constructing the primary tunnel lining with shotcrete on the wire mesh reinforcement and constructing the secondary (final) tunnel lining by pouring fiber added concrete in moving formworks.
D4	The method of constructing the primary tunnel lining with fiber-reinforced shotcrete and building the secondary (final) tunnel lining by pouring concrete in moving formworks after binding the reinforcement of secondary (final) tunnel lining.
D5	The method of constructing the primary tunnel lining with fiber-reinforced shotcrete and constructing the secondary (final) tunnel lining by pouring fiber added concrete in moving formworks.
D6	The method of constructing both primary and secondary (final) tunnel linings by using fiber-reinforced shotcrete.

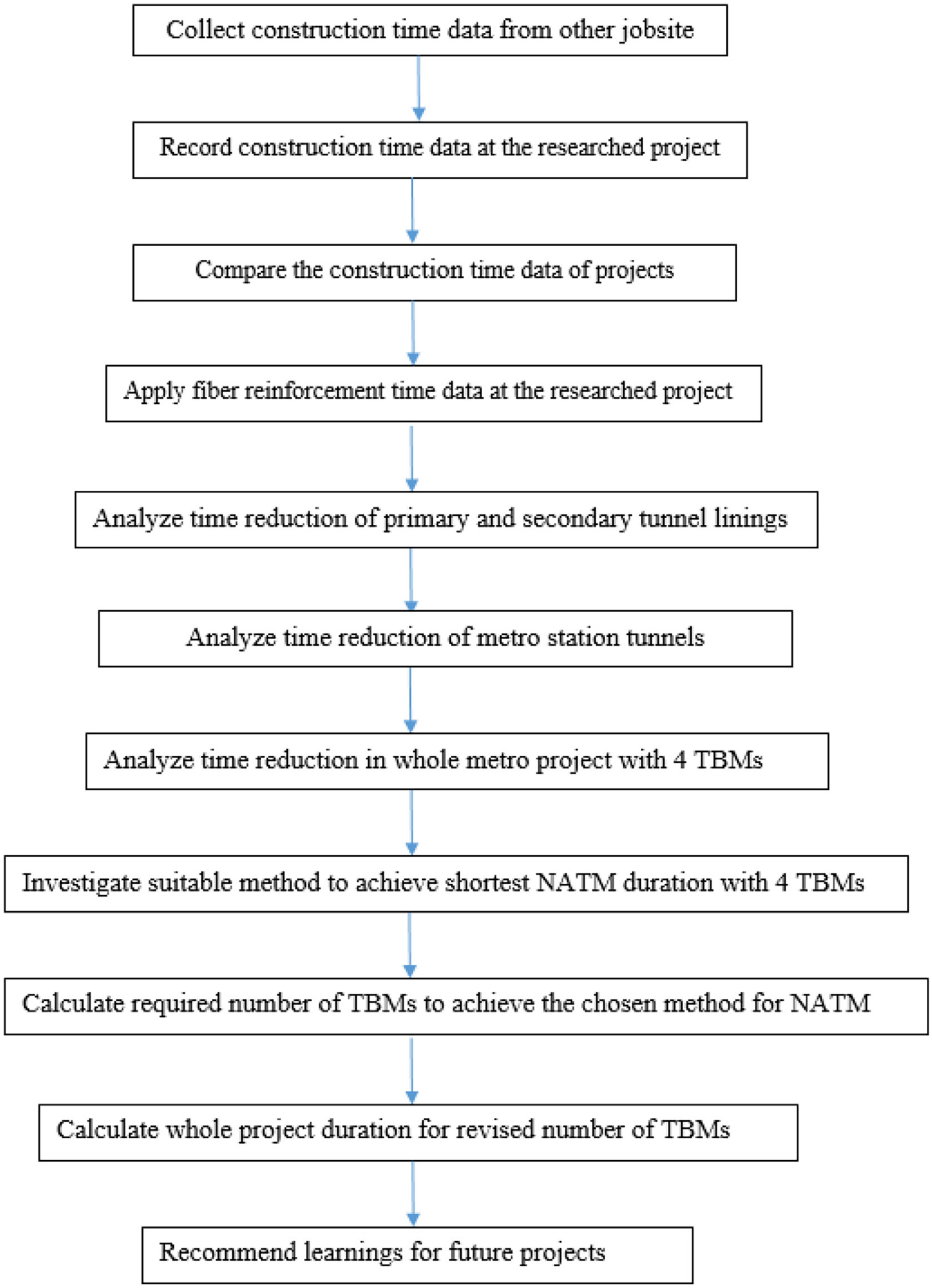

Fig. 1. Methodology.

Istanbul Metropolitan Municipality, is € 563 899 995.32 excluding metro cars. 26 626 m of the tunnels on the line were constructed with TBMs and 10 940 m with NATM (Namli & Aras, 2020).

The tunnels of UUCM project were constructed either by NATM or by using earth pressure balanced tunnel boring machines (EPB-TBMs). In this project, it is planned to bore the mainline tunnels with TBMs, but the rest of the tunnels such as platform, switch, stairway, and depot track tunnels, which have different dimensions from the section of mainline tunnel, are planned to be bored with NATM because it is not possible to bore them with the same TBMs. Some of the stations are constructed by completely cut-and-cover method, while some of them are constructed

Fig. 2. Uskudar-Umraniye-Cekmekoy Metro (UUCM) Line Project Route.

by partly cut-and-cover and partly tunneling methods. The concourse parts of the metro stations are constructed as cut-and-cover, and the remaining parts are constructed as tunnels. The effects of using alternative methods to build primary linings (initial lining for primary support) and secondary (final) linings of platform tunnels, aeration tunnels, stairway tunnels and access tunnels of a metro project on the construction completion time of both the metro stations and the whole metro project are analyzed in this paper.

Çakmak Station has a critical importance in terms of putting Üsküdar-Ümraniye-Çekmeköy Metro Line into service, because Çakmak Station is located in the middle of the whole UUCM line. When the line has been partly put into service, it is going to be used as the terminal station. The construction time of Çakmak Station in UUCM project is analyzed for this purpose.

Three-dimensional plan of Çakmak Station, which is partly constructed as cut-and-cover and partly as tunnel, is shown in Fig. 3. Type P1 tunnel represents the platform tunnel where the passengers wait for the train; Type P2 tunnel is the ventilation connection tunnel; Type B3.1 tunnel is the stairway tunnel; Type B1.2 tunnel is the access (connection) tunnel; Type A is the ventilation tunnel. Plans of existing tunnels at Çakmak Station is depicted at Fig. 4. The plan includes platform tunnels, access tunnels, stairway tunnels and ventilation tunnels. Cross sections of Type P1, P2, B1.2, B3.1 and A tunnels in Çakmak Station are given in Figs. 5 and 6 (IMM, 2013).

Unexpected tunnel collapses could cause significant metro tunnel project delays if they could not be taken under control in time. Hence, it is very important to stop a tunnel collapse at the very beginning of deformations by reacting as soon as possible. In case of unexpected tunnel collapses, utilizing fiber reinforced shotcrete is much

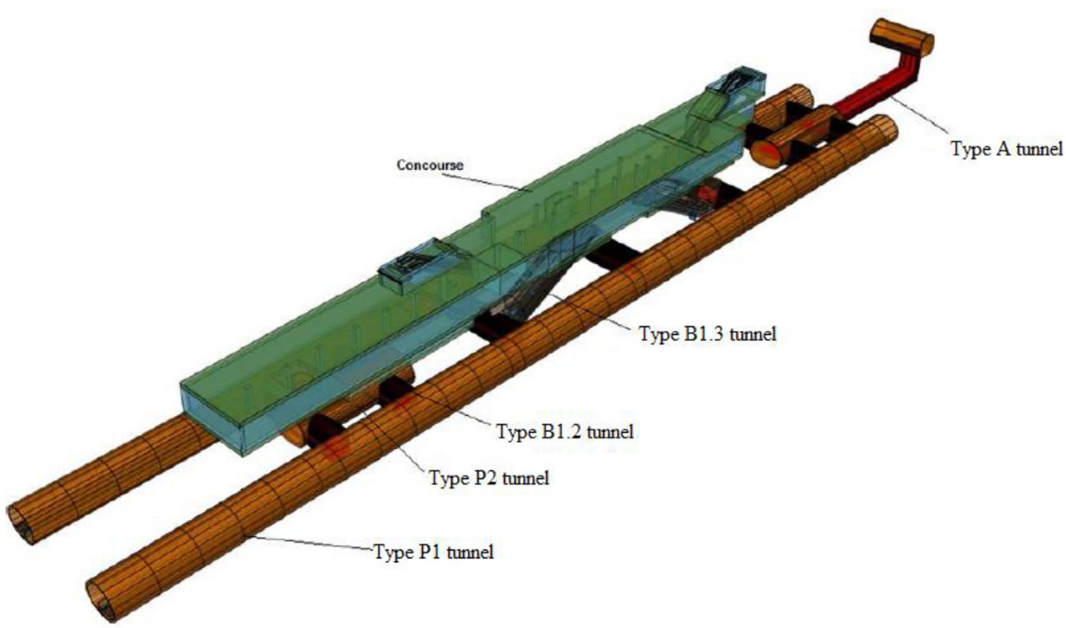

Fig. 3. 3D Image of Çakmak Station (IMM, 2013).

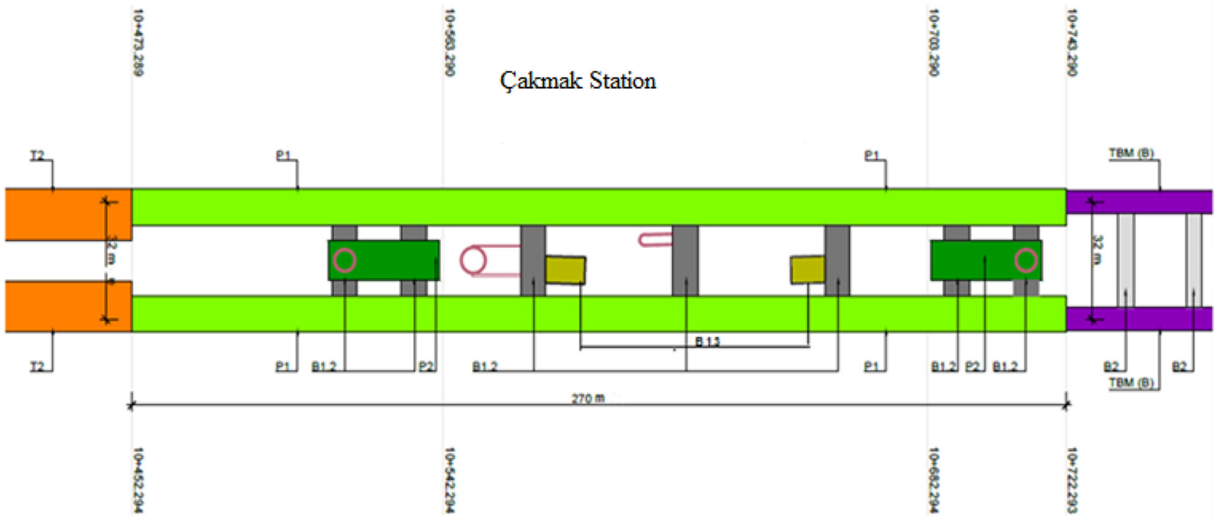

Fig. 4. Çakmak Station tunnel plan (IMM, 2013).

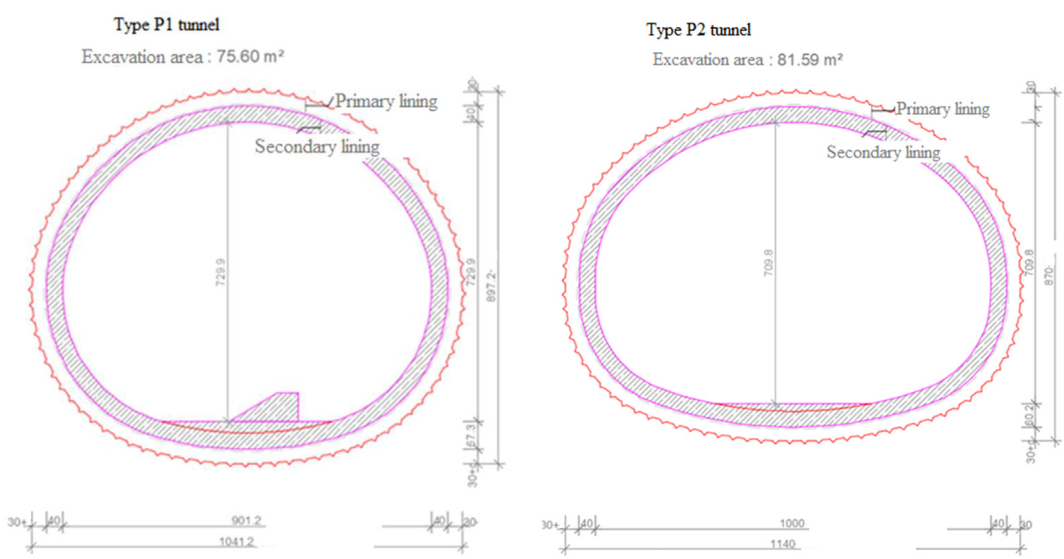

Fig. 5. Cross sections of Type P1 and P2 tunnels (Unit: cm) (IMM, 2013).

faster than shotcrete with wire mesh reinforcement to take the collapse under control.

According to the planned work schedule, the primary (initial) tunnel lining works and the secondary (final) tunnel lining works of the tunnels were targeted to be completed in 770 days (25.5 months), but they were not completed within the specified time. According to the activity reports recorded in the field, only the construction of the tunnels at Çakmak Station lasted approximately 23 months due to the unexpected collapses and the fortification of the ground after these collapses occurred (Araz, 2019). This fact reveals that alternative primary tunnel lining methods are required to complete metro projects on time and put the metro line into service.

4.2 Effect of utilizing fiber reinforced shotcrete for primary tunnel lining

At the first step of this study, using fiber-reinforced shotcrete for primary tunnel lining instead of applying shotcrete on bound wire mesh and eliminating the assembly period of bound wire mesh are investigated. For this purpose, the periods of building primary tunnel lining with bound wire mesh and shotcrete versus with just fiber-reinforced shotcrete implemented in AKHRL Project in Ethiopia are examined. The information obtained from AKHRL Project is compiled from the activity reports regarding the periods of primary lining of the tunnel, which has a cross section area of 66 m^2.

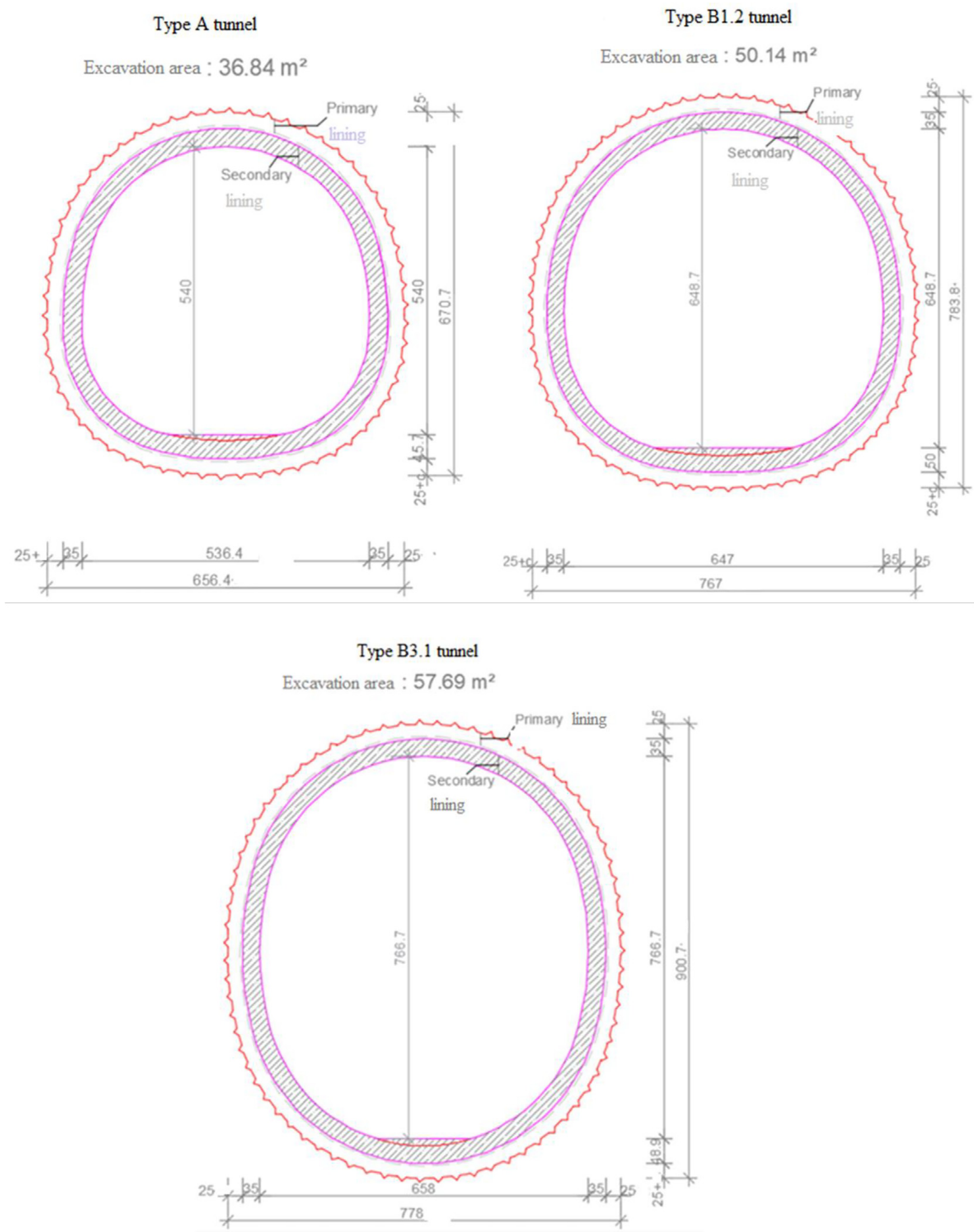

Fig. 6. Cross section of Type A, B1.2, and B3.1 tunnels (Unit: cm) (IMM, 2013).

Table 2
Construction duration of tunnel primary lining with shotcrete on bound wire mesh reinforcement, and that of tunnel primary lining with fiber reinforced shotcrete in Awash-Kombolcha-Haragebeya High-Speed Rail Line (AKHRL) Project.

Method of application	Distance (m)	Period (d)
Primary tunnel lining with shotcrete on the wire mesh reinforcement	40	10
Primary lining constructed with fiber reinforced shotcrete	50	10

The cross section of tunnels of AKHRL Project is similar to that of UUC Metro project. When the jobsite recordings are scrutinized in detail, it is observed that construction duration of tunnel linings are similar between the two projects. Hence, tunnel lining duration with fiber-reinforced shotcrete in primary lining of AKHRL project is taken into consideration for UUCM project analysis. 10-day activity reports of AKHRL project shows that 40 m of the primary tunnel lining were manufactured in 10 days, which served as primary support and was constructed with bound wire mesh, while the progress was 50 m in 10 days when the primary lining serving as primary support was constructed with fiber-reinforced shotcrete (Table 2). Since the period of assembling the bound wire mesh is eliminated by the application of fiber-reinforced shotcrete, there occurs a 20% cutdown of the completion time because the periods needed for bound wire mesh assembly, pin drill and assembly of its iron are taken out. This saving on time is only the time saved from the assembly of a single raw bound wire mesh case. In tunnels supported by double raw bound wire mesh, the time will be saved by application of fiber-reinforced shotcrete will be doubled, so the completion time will be reduced by 40% (Araz, 2019). The reason of this reduction is investigated in UUCM by making an application for 12 m long round and taking the recordings of the duration of sub-activities of primary tunnel lining, such as the time used for binding wire mesh and the time for shotcrete. It is found that the time of labor of reinforcement for primary tunnel lining takes too much time as can be seen in Table 3. In fact, 45% of total time required for building primary tunnel lining is used for binding wire mesh.

This result is coherent with AKHRL project jobsite recordings. This finding is also coherent with those of Covanco Tunnel construction in Brazil and Diversion Tunnels of Gulpur Hydropower Project in Pakistan. Steel fiber reinforced shotcrete was used instead of steel mesh and shotcrete application at Covanca Tunnel, a high-speed motorway project with 96 m^2 cross sectional area, in Rio de Janerio, Brazil. It was reported that the replacement of double raw bond wire mesh with steel fiber reinforcement in primary tunnel lining reduced the construction time of tunnels by 46% (Ortigao et al., 1998). Likewise, in the other project, Sheikh and Saif reported that Steel Fibre-Reinforced Shotcrete (SFRS) was used in the final lining for the Diversion Tunnels of Gulpur Hydropower Project, for the first time in Pakistan. Due to the project schedule constraints, SFRS was used for the side walls up to a height of 1.6 m, and the conventional-reinforced concrete lining was only used in the invert portion. The major advantage of SFRS over conventional lining was reported that SFRS was more than 40% faster to construct compared to conventional tunnel lining, but almost 25% more costly per meter length of tunnel (Sheikh & Saif, 2020).

4.3 Effect of utilizing fiber reinforcement for secondary (final) tunnel lining

At the second step of this study, durations of alternative final tunnel lining applications to build the tunnels of Çakmak station are investigated. Duration of making the final tunnel lining with cast concrete after binding the reinforcement (D1) is recorded (Fig. 7). According to the jobsite recordings of UUCM project, the labors of formwork

Table 3
The jobsite recordings of the labor time of reinforcement for primary lining in UUCM Project.

Method of the station tunnel primary lining (for 75 m^2 tunnel)	Time of binding reinforcement (h)	Time of shotcrete (h)	Total time (h)
Primary lining with wire mesh (for 12 m round)	5.2	6.31	11.51
Primary lining with fiber-reinforced shotcrete (for 12 m round)	0	6.31	6.31

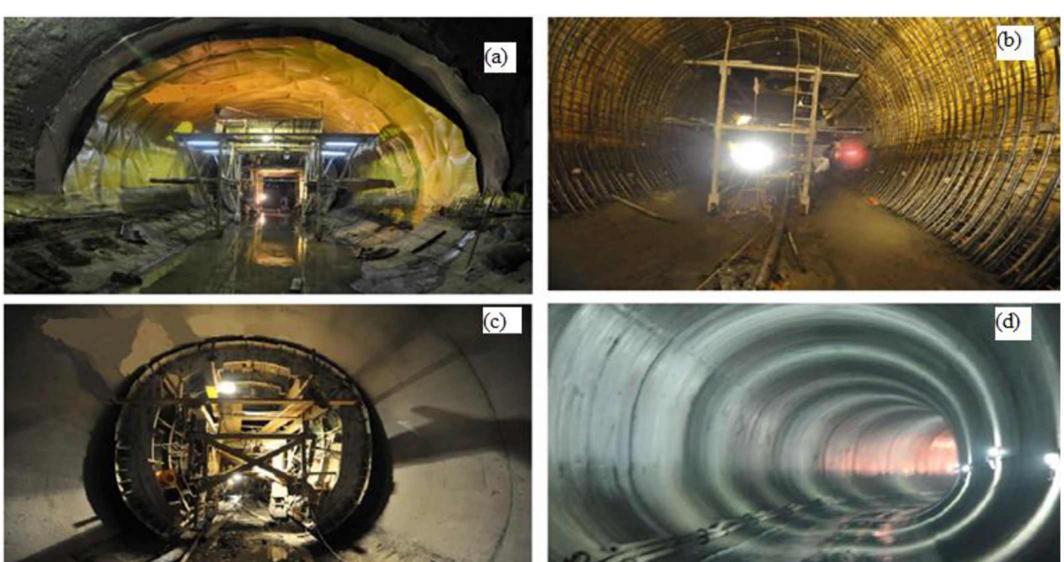

Fig. 7. Stages of tunnel lining with cast concrete (Araz, 2019).

Table 4
The jobsite duration recordings of the labor time of reinforcement binding and the labor of formwork for secondary (final) tunnel lining in UUCM Project (D1).

Construction method of the station tunnel secondary (final) lining (for 75 m^2 tunnel)	Time of cast (h)	Time of binding reinforcement (h)	Cast concrete / Fiber reinforced shotcrete (h)	Total time (h)
Secondary (final) tunnel lining constructed by cast concrete (for 12 m round)	5	8	4	17
Secondary (final) tunnel lining constructed by fiber reinforced shotcrete (for 12 m round)	0	0	8	8

and reinforcement for final tunnel lining take too much time as can be seen in Table 4.

The durations of secondary (final) tunnel linings of various tunnels for Çakmak Station built by cast concrete after binding the reinforcement (D1) are summarized in Table 5, which is prepared according to the jobsite recordings. Durations of making the secondary (final) lining with fiber reinforced shotcrete (D2) and with fiber reinforced cast concrete (D3) are given in Tables 6 and 7, respectively. In fact, 6 months reduction for total secondary lining time of the tunnels at Çakmak Station in Table 6 is reached by non-existence of formwork labor and reinforcement labor times that are given in Table 5.

Furthermore, Table 7 shows the secondary tunnel lining durations at Çakmak Station when the secondary lining is constructed with fiber reinforced cast concrete. When the secondary tunnel lining is constructed with this alternative lining method, the secondary lining of the tunnels at the station can be completed 4 months earlier than that of the secondary tunnel linings constructed with conventional method that utilizes cast concrete. This 4-month period shortening is caused by the non-existence of reinforcement labor. As a result, the positive effect of building the secondary (final) tunnel linings with desired quality of fiber reinforced shotcrete for suitable grounds on planned work schedule makes it possible that fiber reinforced shotcrete emerges as an innovative method to be considered in future metro tunnel projects.

4.4 Effect of utilizing fiber reinforcement for tunnel linings on the construction time of metro station tunnels

At the third step of this research, the effect of utilizing fiber-reinforced shotcrete both for the primary lining of tunnel for support after excavation and for the final lining of tunnel on the duration of Çakmak Station tunnels are investigated. It is observed from both the experience of Awash-Kombolcha-High-Speed Rail Line Project (Table 1) and the jobsite model application in UUCM project (Table 2) that if fiber-reinforced shotcrete is used in primary support system, the primary support period will take 13.8 months as a result of 40% decrease of current 23 months (Araz, 2019). With the goal to determine the effect of accomplishing tunnel lining in a shorter duration

Table 5
Construction durations of secondary (final) tunnel linings of Çakmak station with cast concrete (D1) (Araz, 2019).

Construction durations	Tunnel types				
	P1 platform tunnel	P2 ventilation connection tunnel	B1.2 access tunnel	B3.1 stairway tunnel	A ventilation tunnel
Length (m)	270	32	20	35	75.86
Count	2	2	7	2	1
Time (month)	8.5	1.5	2.5	1.5	2
Total time (month)	16				

Table 6
Construction durations of secondary (final) tunnel linings of Çakmak Station with fiber-reinforced shotcrete (D2) (Araz, 2019).

Construction durations	Tunnel types				
	P1 platform tunnel	P2 ventilation connection tunnel	B1.2 access tunnel	B3.1 stairway tunnel	A ventilation tunnel
Length (m)	270	32	20	35	75.86
Count	2	2	7	2	1
Time (month)	3	0.6	1.05	0.6	0.75
Total time (month)	6				

Table 7
Construction durations of secondary (final) tunnel linings of Çakmak Station with fiber reinforced cast concrete (D3) (Araz, 2019).

Construction durations	Tunnel types				
	P1 platform tunnel	P2 ventilation connection tunnel	B1.2 access tunnel	B3.1 stairway tunnel	A ventilation tunnel
Length (m)	270	32	20	35	75.86
Count	2	2	7	2	1
Time (month)	5.5	1.2	2.3	1.5	1.5
Total time (month)	12				

of time on the entire metro project, the actual work completion durations of UUCM project were recorded (Pakiş, 2017). The mobilization and displacement duration took approximately 2 months.

D1 is the actual tunnel lining case applied at jobsite. D1 consists of building the primary tunnel lining with shotcrete on the wire mesh reinforcement and building the secondary (final) lining by pouring concrete in moving formworks after binding the reinforcement of final lining. The construction duration of all tunnels at the jobsite was recorded on the project schedule by days and months. Although it was targeted to complete the construction of the tunnels at Çakmak Station within 770 days (25.5 months) in the approved work schedule at the beginning of the project, the construction of all tunnels was completed in $2 + 23 + 16 = 41$ months: 2 months for mobilization and infrastructure displacements, 23 months for building the primary tunnel lining for primary support and 16 months for completing the secondary (final) tunnel lining. At the first step of this study, using fiber-reinforced shotcrete for primary tunnel lining instead of applying shotcrete on bound wire mesh and eliminating the assembly period of bound wire mesh was investigated. At the second step, the durations of alternative secondary (final) tunnel lining applications to build the tunnels of Çakmak station were investigated. At the third step, the effect of utilizing fiber-reinforced shotcrete both for the primary lining of tunnel for support after excavation and for the final lining of tunnel on the duration of Çakmak Station tunnels was investigated. It is observed from both the experience of Awash-Kombolcha-High-Speed Rail Line Project (Table 1) and the jobsite model application in UUCM project (Table 2) that if fiber reinforced shotcrete is used in primary support system, as a result of 40% decrease of current 23 months (Araz, 2019), the primary support period will take 13.8 months. The labor time of reinforcement binding and the labor time of formwork(cast) used to build secondary (final) tunnel lining of UUCM project were recorded at jobsite (Table 4). The construction durations of secondary (final) tunnel linings of all tunnels at Çakmak Station were recorded daily at jobsite and transferred to months as shown in Table 5 to be able to check with the work monthly schedule. The duration of building the secondary (final) lining with fiber reinforced shotcrete (D2) was calculated by subtracting both the labor time of reinforcement binding and the labor time of formwork from the total duration, which was 6 months as shown in Table 6. The duration of building the secondary (final) lining with fiber reinforced cast concrete (D3) was calculated as 12 months by subtracting the labor time of reinforcement binding from the total duration, as given in Table 7. To compare construction time difference among various alternatives of fiber reinforcement utilization in primary and secondary (final) tunnel linings, the mobilization time as well as the construction durations of both primary and secondary tunnel linings were given in Table 8. Mobilization time was the same for all cases as 2 months. The derivation of durations in Table 8 was based on Tables 6 and 7. For example, to calculate the duration for D2 case which was the method of constructing the primary tunnel lining with conventional shotcrete on the wire mesh reinforcement and the secondary (final) tunnel lining with fiber reinforced shotcrete, 6 months in Table 6 was used as the duration for secondary lining due to usage of fiber reinforced shotcrete. The construction of primary lining was the same as the actual D1 case but the construction duration.

D3 case was the method of constructing the primary tunnel lining with shotcrete on the wire mesh reinforcement and constructing the secondary (final) tunnel lining by pouring fiber added concrete in moving formworks. The duration of construction of primary lining was the same as that in the actual D1 case, but the construction duration of secondary lining was decreased to 12 months due to no labor of reinforcement binding as given in Table 7.

D4 case was the method of constructing the primary tunnel lining with fiber reinforced shotcrete and building the secondary (final) tunnel lining by pouring concrete in moving formworks after binding the reinforcement of secondary (final) tunnel lining. Due to utilization of reinforced shotcrete at primary lining construction, the duration of primary lining was decreased to 13.8 months as a result of 40% decrease of current 23 months; the secondary lining was the same as that in D1.

D5 case was the method of constructing the primary tunnel lining with fiber-reinforced shotcrete and constructing the secondary (final) tunnel lining by pouring fiber

Table 8
Construction durations of metro station tunnels with various tunnel lining building Methods.

Tunnel lining building methods	Mobilization time (month)	Primary lining time (month)	Final lining time (month)	Total time (month)
The method of constructing the primary tunnel lining with shotcrete on the wire mesh reinforcement and constructing the secondary (final) tunnel lining by pouring concrete in moving formworks after binding the reinforcement of secondary (final) tunnel lining (D1)	2	23	16	41
The method of constructing the primary tunnel lining with conventional shotcrete on the wire mesh reinforcement and the secondary (final) tunnel lining with fiber-reinforced shotcrete (D2)	2	23	6	31
The method of constructing the primary tunnel lining with shotcrete on the wire mesh reinforcement and constructing the secondary (final)tunnel lining by pouring fiber added concrete in moving formworks (D3)	2	23	12	37
The method of constructing the primary tunnel lining with fiber-reinforced shotcrete and building the secondary (final) tunnel lining by pouring concrete in moving formworks after binding the reinforcement of secondary (final) tunnel lining (D4)	2	13.8	16	31.8
The method of constructing the primary tunnel lining with fiber-reinforced shotcrete and constructing the secondary (final) tunnel lining by pouring fiber added concrete in moving formworks (D5)	2	13.8	12	27.8
The method of constructing both primary and secondary (final) tunnel linings by using fiber-reinforced shotcrete (D6)	2	13.8	6	21.8

added concrete in moving formworks. Due to the utilization of reinforced shotcrete at primary lining construction, the duration of primary lining was decreased to 13.8 months and the construction duration of secondary lining was decreased to 12 months. Due to no labor of reinforcement binding, Table 7 is used to calculate duration for secondary lining.

D6 case was the method of constructing both primary and secondary (final) tunnel linings by using fiber reinforced shotcrete. To calculate the construction duration of metro station tunnels in case D6, due to utilization of reinforced shotcrete to both primary and secondary lining, the construction durations of primary and secondary linings decreased to 13.8 months and 6 months (Table 6), respectively. The construction durations of metro station tunnels for various alternatives of fiber reinforcement utilization in primary and secondary (final) tunnel linings (D2, D3, D4, D5, D6) were summarized in Table 8.

4.5 Effect of utilizing fiber reinforcement for tunnel linings on construction time of the whole metro project

At this step of the research, the effects of utilizing fiber-reinforced shotcrete for the primary lining of tunnel for support after excavation and for the secondary (final) lining of tunnel on the duration of the whole metro project are investigated. In UUCM project, the actual average daily progress of 4 TBMs is 11.5 m per day (Namli & Bilgin, 2017), and at this progress rate, the 26 626 m of TBM tunnel can be constructed in approximately 19 months; the mobilization of TBMs takes 6 months, and the access tunnels to be constructed at every 255 m will be completed in approximately 3 months. Therefore, the total TBM tunnels can be completed within 28 months (Table 9).

For the entire UUCM project, the actual work completion periods in the project are recorded and summarized in Table 10, which depicts case D1. The work schedules that depict the cases of D2, D3, D4, D5, and D6 are given in Tables 11–15, respectively.

The start of tunnel electromechanical works requires the completion of the construction of all the tunnels. It is seen from Table 10 (D1) that the most critical activity of the project is the construction of tunnels built by the NATM, and the total completion duration of the project is 60 months. It is seen from Table 11 (D2) that, by building the secondary (final) tunnel lining with fiber shotcrete, the total completion duration of the project decreases to 50 months.

It is seen from Table 12 (D3) that, by pouring fiber added concrete in moving formworks to build the secondary (final) tunnel lining, the total completion duration of the project decreases to 56 months. It is seen from Table 13 (D4) that, by building the primary tunnel lining with fiber-reinforced shotcrete, the total completion duration of the project decreases to 51 months.

Table 9
Construction time of the tunnels which are built by 4 Tunnel Boring Machines (TBMs) at UUCM Project.

Mobilization time (month)	Excavation and segment montage time (month)	Construction time of connection tunnels (month)	Total time (month)
6	19	3	28

Table 10
The actual work completion durations in UUCM Project for D1 (Pakiş, 2017).

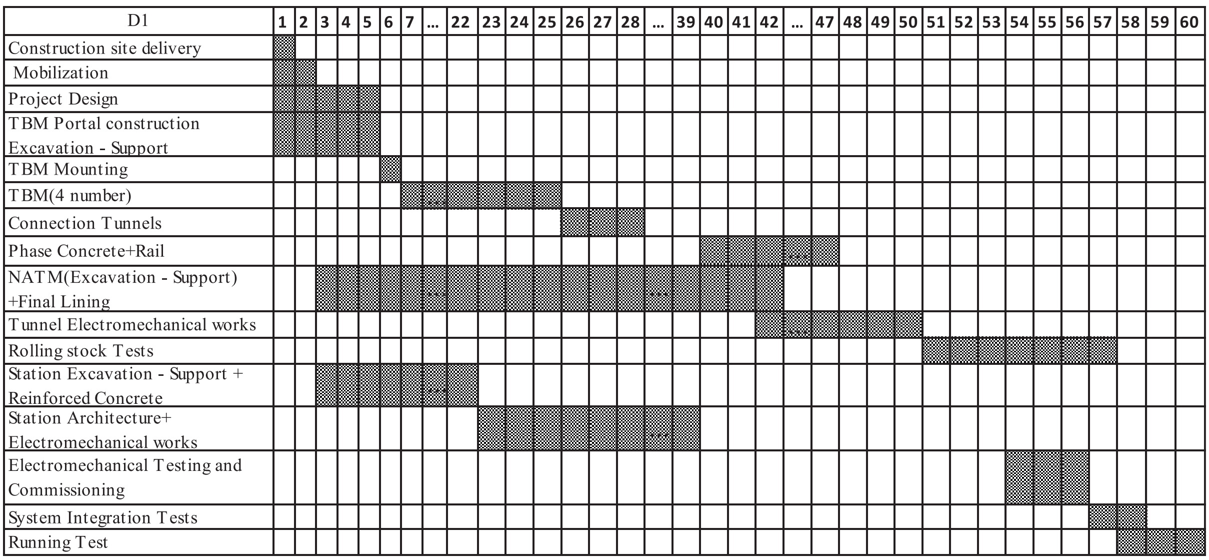

Table 11
The work completion durations in UUCM Project for D2.

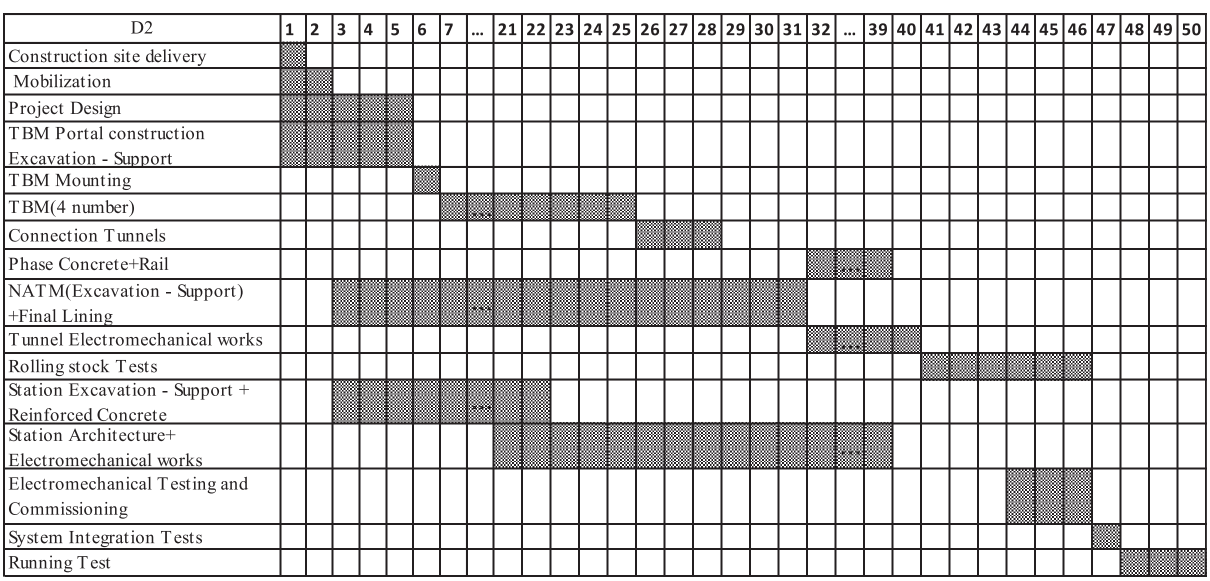

Table 12
The work completion durations in UUCM Project for D3.

D3	1	2	3	4	5	6	7	...	21	22	23	24	25	26	27	28	...	37	38	39	...	45	46	47	48	49	50	51	52	53	54	55	56
Construction site delivery	■																																
Mobilization	■	■																															
Project Design	■	■	■	■	■																												
TBM Portal construction Excavation - Support	■	■	■	■	■																												
TBM Mounting						■																											
TBM(4 number)							■	...	■	■	■	■	■																				
Connection Tunnels														■	■	■																	
Phase Concrete+Rail																			■	■	...	■											
NATM(Excavation - Support) +Final Lining			■	■	■	■	■	...	■	■	■	■	■	■	■	■	...	■															
Tunnel Electromechanical works																			■	■	...	■	■										
Rolling stock Tests																								■	■	■	■	■	■				
Station Excavation - Support + Reinforced Concrete			■	■	■	■	■	...	■	■																							
Station Architecture+ Electromechanical works									■	■	■	■	■	■	■	■	...	■	■	■													
Electromechanical Testing and Commissioning																											■	■	■				
System Integration Tests																														■			
Running Test																															■	■	■

It is seen from Table 14 (D5) that by building the primary tunnel lining with fiber-reinforced shotcrete and the secondary (final) tunnel with pouring fiber added concrete in moving formworks, although the tunnels bored by NATM can be completed in 27.8 months, the total completion time of the project can be decreased to 47 months. Due to 28 months required to construct tunnels by TBMs, the tunnels built by TBMs become more critical.

It is seen from Table 15 (D6) that, by building both primary and secondary (final) tunnel linings with fiber-reinforced shotcrete, although the tunnels bored with NATM can be completed in 21.8 months, the total completion time of the project can be decreased to the minimum, 47 months. Due to 28 months required for tunnels built by TBMs, the tunnels built by TBMs become more critical, too.

Table 13
The work completion durations in UUCM Project for D4.

D4	1	2	3	4	5	6	7	...	21	22	23	24	25	26	27	28	...	32	33	...	39	40	41	42	43	44	45	46	47	48	49	50	51
Construction site delivery	■																																
Mobilization	■	■																															
Project Design	■	■	■	■	■																												
TBM Portal construction Excavation - Support	■	■	■	■	■																												
TBM Mounting						■																											
TBM(4 number)							■	...	■	■	■	■	■																				
Connection Tunnels														■	■	■																	
Phase Concrete+Rail																		■	■	...	■												
NATM(Excavation - Support) +Final Lining			■	■	■	■	■	...	■	■	■	■	■	■	■	■	...	■															
Tunnel Electromechanical works																			■	...	■	■	■										
Rolling stock Tests																								■	■	■	■	■	■				
Station Excavation - Support + Reinforced Concrete			■	■	■	■	■	...	■	■																							
Station Architecture+ Electromechanical works									■	■	■	■	■	■	■	■	...	■	■	...	■												
Electromechanical Testing and Commissioning																											■	■	■				
System Integration Tests																														■			
Running Test																															■	■	■

Table 14
The work completion durations in UUCM Project for D5.

D5	1	2	3	4	5	6	7	…	21	22	23	24	25	26	27	28	29	…	36	37	38	39	40	41	42	43	44	45	46	47
Construction site delivery	■																													
Mobilization	■	■																												
Project Design	■	■	■	■	■																									
TBM Portal construction Excavation - Support	■	■	■	■	■																									
TBM Mounting						■																								
TBM(4 number)							■	■ …	■	■	■	■	■																	
Connection Tunnels														■	■	■														
Phase Concrete+Rail																	■	■ …	■											
NATM(Excavation - Support) +Final Lining			■	■	■	■	■	■ …	■	■	■	■	■	■	■	■														
Tunnel Electromechanical works																	■	■ …	■	■										
Rolling stock Tests																					■	■	■	■	■	■				
Station Excavation - Support + Reinforced Concrete			■	■	■	■	■	■ …	■	■																				
Station Architecture+ Electromechanical works									■	■	■	■	■	■	■	■	■	■ …	■	■	■	■								
Electromechanical Testing and Commissioning																								■	■	■				
System Integration Tests																											■			
Running Test																												■	■	■

Table 15
The work completion durations in UUCM Project for D6.

D6	1	2	3	4	5	6	7	…	21	22	23	24	25	26	27	28	29	…	36	37	38	39	40	41	42	43	44	45	46	47
Construction site delivery	■																													
Mobilization	■	■																												
Project Design	■	■	■	■	■																									
TBM Portal construction Excavation - Support	■	■	■	■	■																									
TBM Mounting						■																								
TBM(4 number)							■	■ …	■	■	■	■	■	■	■	■														
Connection Tunnels														■	■	■														
Phase Concrete+Rail																	■	■ …	■											
NATM(Excavation - Support) +Final Lining			■	■	■	■	■	■ …	■																					
Tunnel Electromechanical works																	■	■ …	■	■										
Rolling stock Tests																					■	■	■	■	■	■				
Station Excavation - Support + Reinforced Concrete			■	■	■	■	■	■ …	■	■																				
Station Architecture+ Electromechanical works									■	■	■	■	■	■	■	■	■	■ …	■	■	■	■								
Electromechanical Testing and Commissioning																								■	■	■				
System Integration Tests																											■			
Running Test																												■	■	■

Table 16
The work completion durations in UUCM Project for D6 with 6 TBMs.

D6	1	2	3	4	5	6	7	…	19	20	21	22	…	28	29	30	31	32	33	34	35	36	37	38	39	40	41
Construction site delivery																											
Mobilization	■	■																									
Project Design	■	■	■	■	■																						
TBM Portal construction Excavation - Support	■	■	■	■	■																						
TBM Mounting						■																					
TBM(6 number)							■	...	■																		
Connection Tunnels										■	■	■															
Phase Concrete+Rail											■	■	...	■													
NATM(Excavation - Support) +Final Lining			■	■	■	■	■	...	■	■	■																
Tunnel Electromechanical works												■	...	■	■	■											
Rolling stock Tests																	■	■	■	■	■	■					
Station Excavation - Support + Reinforced Concrete			■	■	■	■	■	...	■	■	■	■															
Station Architecture+ Electromechanical works											■	■	...	■	■	■	■	■	■	■	■	■	■	■	■		
Electromechanical Testing and Commissioning																					■	■	■				
System Integration Tests																								■			
Running Test																									■	■	■

4.6 Analysis of the required number of TBMs to minimize the construction time of metro projects

At the last step of this study, it is observed that using fiber reinforcement in tunnel lining cause a meaningful decrease on construction time of metro tunnels. Fiber reinforced shotcrete utilized for primary and final lining of NATM tunnels can be constructed in 21.8 months (Table 8). However, if the number of TMBs are not adequate, even though the NATM tunnels are able to be completed by 21.8 months, TBM tunnels could not be completed before 28 months with 4 TBMs. A back analysis is performed to find the required number of TBMs so as to complete TBM tunnels within the same time frame of completing NATM tunnels. The length of total TBM tunnels is 26 626 m. Except that the mobilization of TBMs takes 6 months and the access tunnels to be constructed at every 255 meters are completed in approximately 3 months, the time for excavation of TBM tunnels is 21.8 – 9 = 12.8 months, in other words, 384 days. To complete the TBM tunnels within 12.8 months, the least required total TBMs average daily progress should be 26626/384 = 69 m/d. According to Namli and Bilgin (2017), actual daily average progress of a TBM, utilized in UUCM project is 11.5 m. Hence, the number of TBMs required to complete total TBM tunnels within 12.8 months is 69/11.5 = 6 TBMs.

If 6 TBMs are used, then in this case, tunnel constructions are able to be completed in 41–21.8 = 19.2 months earlier than that by the conventional practice (D1), which means that a total metro project such as UUCM project can be completed in 60–19.2 = 40.8 months within 42 months target project duration, in other words, within

Table 17
Cost comparison for tunnel linings with and without fiber reinforced shotcrete in Çakmak Station Tunnels.

Station (NATM) tunnel costs for tunnel linings with and without fiber reinforced shotcrete	Total Cost (€)
The method of constructing the primary tunnel lining with shotcrete on the wire mesh reinforcement and constructing the secondary (final) tunnel lining by pouring concrete in moving formworks after binding the reinforcement of secondary (final) tunnel lining (D1)	3 374 757.19
The method of constructing both primary and secondary (final) tunnel linings by using fiber-reinforced shotcrete (D6)	2 814 387.30
Reduction in cost with the use of fiber reinforced shotcrete (D1 – D6)/D1	16.6%

Table 18
Cost comparison for tunnel linings with and without fiber reinforced shotcrete in UUCM metro tunnels.

Metro (NATM) tunnel costs for tunnel linings with and without fiber reinforced shotcrete	Total cost (€)
The method of constructing the primary tunnel lining with shotcrete on the wire mesh reinforcement and constructing the secondary (final) tunnel lining by pouring concrete in moving formworks after binding the reinforcement of secondary (final) tunnel lining (D1)	18 578 417.40
The method of constructing both primary and secondary (final) tunnel linings by using fiber-reinforced shotcrete (D6)	15 852 415.55
Reduction in cost with the use of fiber reinforced shotcrete (D1 – D6)/D1	14.7%

3.4 years (Table 16) instead of actual project completion duration 5 years (Table 10).

4.7 Cost comparison for tunnel linings with and without fiber reinforced shotcrete

Based on a comprehensive data collected from jobsite and authors' work, utilizing fiber reinforcement to construct both the final lining and the primary lining of tunnels reduces construction cost of the metro station tunnels by 16.6%, which is summarized at Table 17. Utilizing fiber reinforcement to construct both the final lining and the primary lining of tunnels reduces the construction cost of the metro tunnels by 14.7%. This comparison is summarized at Table 18.

5 Discussions

Based on a comprehensive data collected from jobsite, this research revealed, first of all, if fiber reinforced shotcrete is used to construct the primary lining of the tunnels instead of double raw bound wire mesh, then the time required for the assembly of double raw bound wire mesh is eliminated, and in turn, 40% time decrease of construction of primary support system can be achieved.

Secondly, from the result of recordings made on the field and the comparison of alternative lining applications, it is seen that secondary (final) linings of the metro station tunnels with cast concrete after binding the reinforcement (D1) can be completed in 16 months, while secondary (final) linings of the metro station tunnels can be completed in 6 months if they are built with fiber reinforced shotcrete (D2). In addition, if the secondary (final) linings of the metro station tunnels are built by casting the concrete with fiber instead of conventional concrete steel (D3), the construction completion time of secondary (final) lining of metro stations can be 12 months.

Thirdly, the method of building the primary tunnel lining with conventional shotcrete on the wire mesh reinforcement and the secondary (final) tunnel lining with fiber-reinforced shotcrete (D2) requires 31 months. The method of building the primary tunnel lining with shotcrete on the wire mesh reinforcement and building the secondary (final) tunnel lining by pouring fiber added concrete in moving formworks (D3) requires 37 months. The method of building the primary tunnel lining with fiber-reinforced shotcrete and building the secondary (final) tunnel lining by pouring concrete in moving formworks after binding the reinforcement of secondary (final) tunnel lining (D4) requires 31.8 months. Even though using fiber reinforced shotcrete in the final lining (D2) looks 24 days (0.8 months) shorter than the case D2, it should be kept in mind that the quality control level required for final tunnel lining in the usage of fiber reinforced shotcrete is higher than the case of fiber reinforced shotcrete used in primary tunnel lining. Furthermore, the method of building the primary tunnel lining with fiber-reinforced shotcrete and building the secondary (final) tunnel lining by pouring fiber added concrete in moving formworks (D5) requires 27.8 months, so this becomes a faster alternative than D2, D3 and D4.

In addition, the actual total construction completion time of Çakmak Station was 41 months (D1). When fiber-reinforced shotcrete is used in both primary and secondary (final) linings of the tunnels, it is determined that 21.8 months total construction time (D6) can be achieved. This means that construction completion time of the Çakmak Station can be reduced by 47% as compared to conventional method of primary support and cast concrete.

Furthermore, the completion of the tunnels which are bored with 4 TBMs requires 28 months. Even though boring and lining of the tunnels built by NATM can be completed in 21.8 months by alternative methods, total tunnel construction time can be decreased down to minimum 28 months from 41 months; because the tunnels built by TBMs become the critical activity of the project and the electromechanical works of the tunnels on the metro line can be started after the completion of all tunnels. Hence, it is possible to put an entire metro project, such as at UUCM project with 4 TBMs, into service 13 months earlier than the conventional practice, D1.

All in all, if fiber reinforced shotcrete is utilized for the construction of both primary and secondary lining of tunnels which are not bored by TBMs, it is determined that TBM excavation performance becomes the critical activity of metro project, in other words, TBM excavation becomes predominant factor for finalizing metro tunnel construction works. For example, instead of 4 TBMs, if 6 TBMs are utilized in UUCM project, then the tunnel constructions can be completed 41–21.8 = 19.2 months earlier than that in the conventional practice, which means that a metro project such as UUCM project can be completed within 3.4 years instead of 5 years. This means that a metro project, like UUCM project with 5-year construction time, can be put into service within 32% less time.

6 Contributions to the body of knowledge

Although there have been cases of adaptation of tunnel linings with fiber reinforcement, there is not any specific study that evaluates the constructions of both NATM tunnels and TBM tunnels together to complete whole metro tunnel project within the target completion duration. Even though the target completion time of the investigated metro project was 42 months, it was completed in 60 months.

The new perspective of this study is to analyze the effect of utilization of fiber reinforcement at NATM tunnel linings on a whole metro project duration by evaluating construction time of NATM tunnels and TBM tunnels all together. In case of no fiber reinforcement was used, the most determinant (critical) activity of the project is the construction of NATM tunnels. If NATM tunnels are not completed, the tunnel electromechanical works could not be started because the start of tunnel electromechanical works require the completion of the construction of all the tunnels. Hence, it has no meaning to complete TBM tunnels by increasing the numbers of TBMs alone. By utilizing fiber reinforcement for the construction of both primary and final tunnel linings of NATM tunnels, TBM tunnels become the determinant (critical) activity of a whole metro tunnel project instead of NATM tunnels. Since TBM tunnels become the critical activity of a project, big metro projects can be completed within the targeted project durations by ordering required number of TBMs at the very beginning of the planning stages.

To predict the required number of TBMs in metro tunnel construction works to complete metro projects on time, it is recommended to consider the utilization of fiber reinforced shotcrete at the very beginning of planning work schedules. If fiber reinforced shotcrete will be applied to primary and secondary (final) lining of tunnels, then the tunnel construction activity becomes more mechanically controllable, because TBM tunnel excavation become a determinant (critical) activity in the whole tunnel construction duration. Predicting the required number of TBMs at the very beginning of the planning stages leads to not only a more accurate budget but also a more predictable tunnel construction time frame, which is very important for big metro projects.

This study reveals that using reinforced shotcrete to build primary and final tunnel linings can provides a great advantage in terms of cost and duration for metro projects, if the required labor and construction quality for shotcrete applications are ensured.

7 Conclusions

Based on the comprehensive data collected from the jobsite and the authors' work, it is concluded that utilizing fiber reinforced shotcrete to construct either the primary linings or the secondary (final) linings of metro station tunnels reduces the construction time of station tunnels by approximately 25%. In addition, using fiber reinforcement to construct both the final lining and the primary lining of tunnels reduces the construction time of metro station tunnels and the whole metro project by 47% and 22%, respectively. From viewpoint of cost, utilizing fiber reinforcement to construct both the final lining and the primary lining of tunnels reduces the construction cost of the metro station tunnels and construction cost of the metro tunnels by 16.6% and 14.7%, respectively.

Further research reveals that even though using fiber reinforcement in tunnel lining causes a substantial reduction in construction time of metro tunnels, it is not adequate to use fiber reinforcement in tunnel lining alone to complete the metro project within the targeted project duration. To complete metro projects on time, the number of TBMs should be also adequate that can complete TBM tunnels within the same completion duration of the NATM tunnels, in which fiber reinforced shotcrete is utilized for the construction of both primary and final tunnel linings.

Overall, utilizing fiber reinforced shotcrete to construct linings of metro tunnels reduces not only the construction time but also the construction cost of metro projects. To be able to put into service the whole metro projects within the target project time, the required number of the TBMs should be predicted prior to the execution of the metro projects by synchronizing the TBM tunnels construction time with the construction time of the NATM tunnels utilizing fiber reinforced shotcrete.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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