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Research paper

Application of shotcrete constitutive model to the time dependent behavior of TBM tunnel lining

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Abstract

Shotcrete is ordinary concrete applied to the surface under high pressure. It demonstrates a highly time-dependent behaviour after few hours of application. Traditional approaches assume a simple linear elastic behaviour using a hypothetical young modulus to investigate the time-dependency and creep effects. In this paper, a new constitutive model of shotcrete is applied to evaluate the time-dependent behaviour of a TBM tunnel lining and investigate the parameters that can influence this behaviour. The Shotcrete model is based on the framework of Elasto-plasticity and designed to model shotcrete linings more realistically. The basic data of Pahang-Selangor Raw Water Transfer Project is used for the analysis study. An attempt is made to investigate the influence of some input parameters of the shotcrete model on the time-dependent behaviour of the shotcrete lining. These parameters include the time-dependent stiffness/strength parameters, creep and shrinkage parameters and steel fibre parameters. The variation in shotcrete strength classes causes a noticeable influence on the development of shotcrete compressive strength with time, particularly during the first days of application. The creep and shrinkage strain cause a considerable reduction in the development of the shotcrete stress with time. The impact of steel fibre content is determined, and the result indicated that the development of plain shotcrete stresses with time is lower than that of the reinforced shotcrete. In addition, a comparison study is performed to analyse the tunnel lining behaviour using both shotcrete model and an elastic analysis. Significant differences in shotcrete lining stresses are achieved when using the elastic analysis while the shotcrete model results in a reasonable result that can be used for the design requirements.

Keywords: *Creep and Shrinkage; Shotcrete Model; Shotcrete Stress; Steel Fiber; Time-Dependent Behavior.*

1. Introduction

During excavation, the underground openings need to be supported to stabilize and secure the rock mass, this can be achieved by several types of rock support elements. The most important and common support types used are shotcrete, fibre reinforced and unreinforced. Shotcrete is a special type of concrete conveyed through a hose at high pressure onto a surface to shape different structural elements such as walls, floors, and roofs. Shotcrete must be applied immediately after excavation due to its ability to resist disturbances and carry loads early after installation. In conjunction with the conventional casting methods, shotcrete can be used in many structural materials due to high strength, durability, low permeability, excellent bond, limitless shape possibilities, and an economical and well-established substitution technique. The hardened properties of shotcrete are similar to the traditional cast-in-place concrete, but the shotcrete application process provides additional advantages, including the superior bond with most substrates and immediate or rapid capabilities, especially in case of irregular shapes and forms. In general, concrete is weak in tension and strong in compression and tends to be a brittle material. Fibres are strong in tension thus, adding the fibres could enhance many significant properties of shotcrete such as the ductility, energy absorption, impact resistance as well as time and cost saving. Shotcrete ductility is the ability to carry loads after the matrix has cracked [1]. There are several types of fibres used in concrete mixes such as; steel, plastic, wood, carbon, glass, and cellulose. According to Zollo [2], the fibre effect plays a key role in the nature of energy absorption and crack control than in the load transfer capacity. In case of primary tunnel lining, the use of steel fibre reinforced shotcrete is very common more than the reinforcement mesh and the steel arches. Furthermore, using steel fibre reinforced shotcrete could improve the safety of workers near the excavation face and eliminate the material and time needed for tunnel construction [3]. With the rapid development of underground structures, Shotcrete became the fundamental elements used in hard rock tunnelling. It is used widely in all types of engineering projects, which require limited access space, minimum formwork and difficult-to-reach areas. Generally, the shotcrete material shows a time-dependent behaviour after few hours of application leading to possible stress levels within the lining which are comparatively high or approaching the failure. It is important to predict the time-dependent behaviour of shotcrete material to investigate the ultimate and serviceability limit states during tunnel construction [4]. During the cement hydration process, the shotcrete material behaviour develops with time, resulting in a sophisticated stress-strain curve history in tunnel lining [5]. The mechanical interaction between the tunnel lining and the surrounding rock mass is dominated by the change of early age properties of shotcrete material with time. The increase in stiffness and strength of the hardening cement paste with time is attended by an increase in temperature due to the hydration energy generation. In addition, complicate stress conditions can result from the creep, relaxation and shrinkage mechanisms. The shotcrete primary supports are loaded early thus, the effect of time-dependent material properties on the deformation and load bearing capacity is more important than the ordinary concrete. After application, shotcrete material displays plastic and ductile behaviour with low stiffness and strength. As the stiffness and strength increase with time, the shotcrete material becomes more brittle [6].

In this paper, a constitutive model of shotcrete is performed in a numerical analysis of a TBM tunnel lining of Pahang-Selangor Raw Water Transfer Project. The shotcrete model is based on the framework of Elasto-plasticity and can be used for shotcrete, cast concrete, jet grout and any cement-based materials. Furthermore, it accounts for the non-linear and time-dependent behaviour of cement material. Shotcrete model required a number of input parameters, so in this study, the effect of some of these parameters on the time-dependent behaviour of the shotcrete lining is estimated. These parameters include the time-dependent stiffness/strength parameters, creep and shrinkage parameters and steel fibre parameters. A parametric study is performed by deactivating the model features separately and their effect on the development of the shotcrete lining stiffness, strength, stress, and displacement with time is investigated. In addition, a comparative study is performed to identify the difference between the non-linear and linear elastic behaviour of the tunnel lining. Therefore, the steel fibre reinforced shotcrete lining is analysed in term of major stresses and vertical displacement using both of shotcrete model and an elastic analysis method. A constant young modulus of elasticity of 28 MPa is assumed for the elastic analysis method.

2. Shotcrete constitutive model

Shortly after application, shotcrete linings undergo a high load while the ordinary concrete is not fully hardened yet. Therefore, the time-dependent behaviour of the shotcrete material must consider. There are many models in the literature used in the practice and performed in numerical modelling to describe the concrete behaviour, more details about these models are available in Thomas 2009 [7]. These methods include the rheological models, models with simple power laws for creep, Hypothetical Modulus of Elasticity methods and Rate of Flow method. The creep effect, which has a considerable influence on the stresses of the shotcrete lining, has been considered in those models. In this work, the shotcrete lining is modelled by means of the constitutive model of shotcrete which has been developed and implemented in Plaxis 2D software by Brinkgreve et al. 2012 [8]. It is based on the framework of Elasto-plastic strain hardening/softening plasticity and can be used for any cement-based materials such as shotcrete, cast concrete, jet grout etc. The need for such model is raised since the traditional engineering approaches assume a linear elastic method with a gradual increase of shotcrete stiffness to simulate the tunnel lining in numerical modelling uses. This approach cannot predict the time-dependent ductility of shotcrete and results in high internal forces [9], [10], and [11]. In the shotcrete model, continuum elements are used to model the shotcrete lining in which the user is enable to investigate the time-dependency of stiffness, strength, creep and shrinkage effects, as well as the plastic deformation before and after achieving the maximum strength. Determining the hardening and post-peak softening behaviour in tension and in compression is one of the functions of this model [10]. The model formulation is explained in detail by Schaedlich, and Schweiger [10] and Schaedlich et al. [11] and a brief description is provided in this work. The input parameters of this model are listed in Table 3.

Shotcrete model uses both of Mohr-Coulomb yield surface for deviatoric loading and Rankine yield surface in the tensile regime. Plastic strains are calculated according to strain hardening/softening Elasto-plasticity. The total strain includes the sum of elastic strain ε^{e}, plastic strain ε^{p}, creep strain ε^{cr} and shrinkage strain ε^{shr}, as in Eq. (1)

$$\varepsilon = \varepsilon^{e} + \varepsilon^{p} + \varepsilon^{cr} + \varepsilon^{sh} \tag{1}$$

The shotcrete stiffness and strength increase immediately with time due to the hydration process of the cement paste. The development of shotcrete stiffness with time follows the recommendation of CEB-FIP model code (1990) [12]:

$$E(t) = E_{28}\, e^{S_{stiff}\ (1-\sqrt{28/t})} \tag{2}$$

$$s_{stiff} = -\frac{\ln(E_1 / E_{28})}{\sqrt{28}-1} \tag{3}$$

Where E_{28} represents the young's modulus at 28 days and E_1indicates the young's modulus at 1 day. S_{stiff} is related to the stiffness ratio at 1 day and t_{hyd}, E_1/E_{28}. Furthermore, the S_{stiff} parameter controls the variation of stiffness with time. The evolution of shotcrete strength up to 24h can be achieved according to the early strength classes J1, J2 and J3 provided by EN 14487-1 [13] and shown in Fig. 1. The shotcrete model considers the mean values of the classes defined in the standard. The purpose of each class is summarized as follow:

Class J1: It is appropriate to use for the thin layers of shotcrete or in dry surfaces. No structural requirements are to be expected shortly after installation.

Class J2: Shotcrete of this class is used when thicker layers are required to achieve within a brief time. In addition, it can use for vertical, overhear and difficult surfaces.

Class J3: Due to its fast setting and high dust and rebound occur within the application, this class is used only in particular cases, e.g. high ground water pressures, very rapid tunnel advance, etc.

However, Oluokun [14] suggested an approach to calculate the shotcrete strength between 24h and t_{hyd}:

$$\mathrm{F_{c(t)}} = \mathrm{F_{c,28}} \cdot \left(\frac{\mathrm{F_{c,1}}}{\mathrm{F_{c,28}}}\right) . [(\mathrm{t_{hyd}} - \mathrm{t})/(\mathrm{t_{hyd}} - 1\ \mathrm{day}).\mathrm{t}] \tag{4}$$

Where $\mathrm{F_{c,1}}$ and $\mathrm{F_{c,28}}$ are the compressive strength of shotcrete after 1and 28 days respectively. t_{hyd} is the time for full curing (usually 28 days) and t is a time in days. Creep is modelled according to a viscoelastic approach. Creep strains ε^{cr} show linearly increase with stress σ as:

$$\varepsilon^{cr}(t) = \frac{\varphi^{cr}\sigma}{D} \frac{(t - t_{\circ})}{(t + t_{50}^{cr})} \tag{5}$$

Where φ^{cr} and D are the creep factor and the linear elastic stiffness matrix respectively, $\mathrm{t_0}$ is the loading time and $t_{50}^{cr}$is the required time to develop 50% of creep strain. In case of shotcrete utilization more than 45% of f_c, non-linear creep effects can be calculated by an equation provided by EC2 [15]. According to the recommendation of ACI 209-R92 [16], the Shrinkage strain ε^{shr}can be found as:

$$\varepsilon^{shr}(t) = \varepsilon_{\infty}^{shr}\left(\frac{t}{t + t_{50}^{shr}}\right) \tag{6}$$

Here $\varepsilon_{\infty}^{shr}$is the final shrinkage strain and the t_{50}^{shr} related to the time of %50 of shrinkage strain.

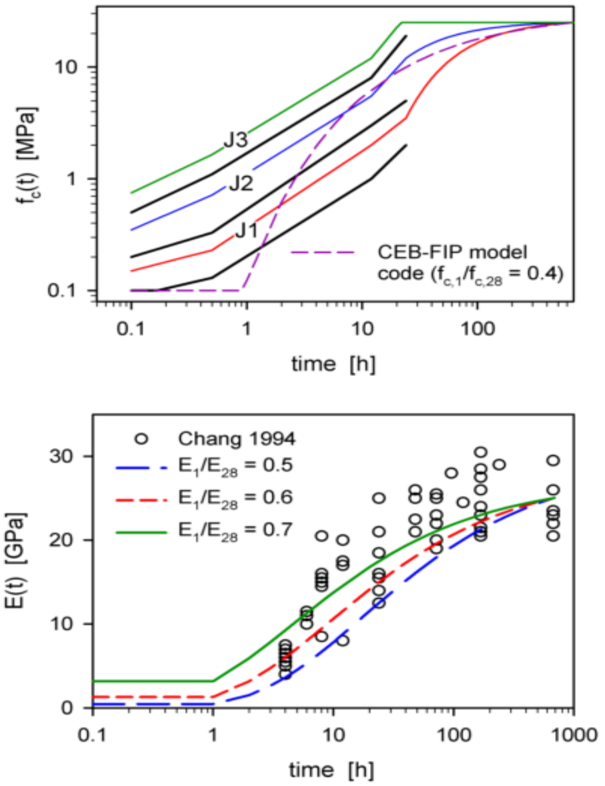


Fig. 1: Evaluation of Shotcrete Strength and Stiffness with Time [17].

3. Case study

The steel fibre reinforced shotcrete lining of the water tunnel of the Pahang-Selangor raw water project is analysed to investigate its time-dependent behaviour and determine the factors that influence this behaviour. This project is in the central zone of Peninsular Malaysia and connects the states of Pahang and Selangor through a long water transfer tunnel (see Figure 2). Its function is to provide about 1.89 billion litres of water per day to the state of Selangor and the Federal Territories of Kuala Lumpur and Putrajaya. Consequently, it relieved the shortage of water supply for daily life and industries. It is one of the largest infrastructure projects in Asia. The tunnel length is 44.6 km with 5.2 m diameter. It was excavated using three TBMs (TBM 1, TBM 2, and TBM 3) for about 35 km of the whole tunnel length by 1,200 m deep. The conventional tunnel excavation method (NATM) has been used to excavate 4 sections of the total 9.1 km long while the Cut and Cover Method used to excavate one section of 0.9 km long. The deepest section is 1,246 m and about 5,000 m of the tunnel has over 1,000 m deep [18]. Along the entire tunnel length, the type of the rock mass is granite. In this work, the shotcrete lining of TBM-2 section at Ch. 23048 m, as shown in Fig. 3, is selected for the numerical analysis.

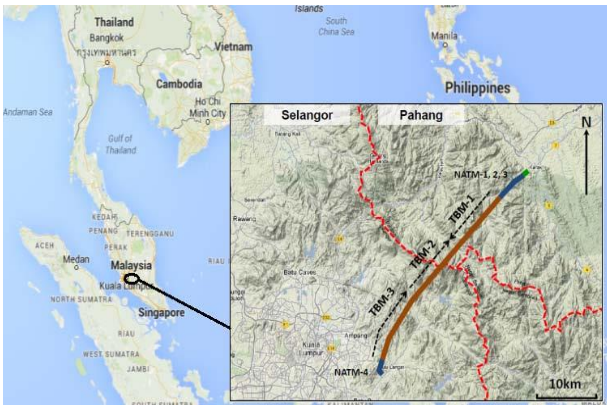


Fig. 2: Tunnel Structure of Pahang-Selangor Raw Water Transfer Tunnel [19].

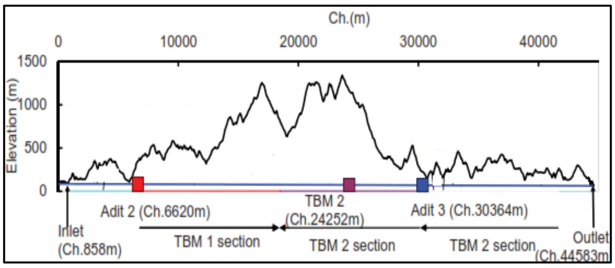


Fig. 3: Cross Section of Pahang-Selangor Water Transfer Tunnel.

4. Methodology

4.1. Numerical modelling

A parametric analysis of TBM tunnel lining is presented using a plane-strain finite element program Plaxis 2D. The geometric model and finite element mesh are presented in Fig. 4. The tunnel diameter is 5.2 m. The model boundary is adapted to 10 times of the tunnel diameter to reduce the boundary effects [20]. A circular geometry of 20 m is introduced around the tunnel to refine the mesh locally. A fine mesh is used around the tunnel to enhance the accuracy of the stress analysis. Granite is the type of the rock mass along Pahang-Selangor water transfer tunnel project. The average unit weight and Poisson's ratio of the rock are 26.7 KN/m^3 and 0.2, respectively. The equivalent Mohr-Coulomb model is used to simulate the behaviour of the rock mass surrounding the tunnel. The input parameters for the equivalent Mohr-Coulomb model used in this analysis are listed in Table 1.

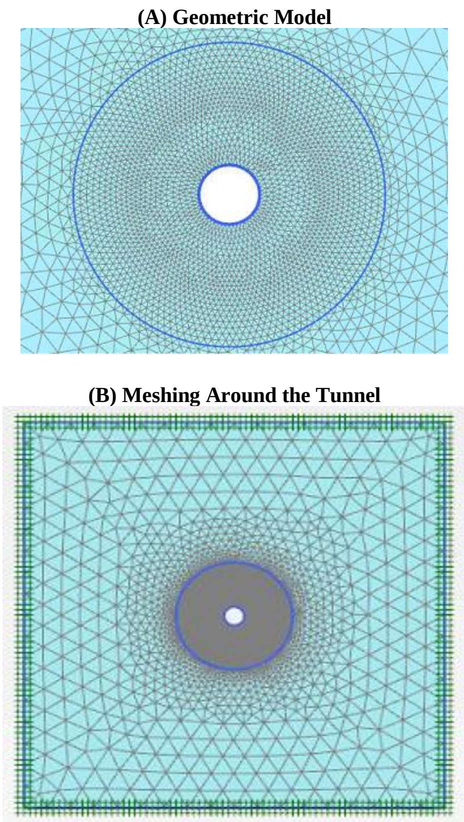


Fig. 4: A) Geometric Model, B) Mesh around the Tunnel.

Table 1: Input Parameters for the Equivalent Mohr-Coulomb Model

Item	Unit	Value
Young Modulus E	MPa	35516.163
Poisson ratio ν	-	0.2
Friction angle ϕ_m	°	52.34
Cohesive strength C_m	MPa	6.239
Unit weight γ_d	KN/m^3	26.7

4.2. Tunnel lining system

The tunnel was supported using a sprayed steel fibre reinforced shotcrete lining. The lining thickness is about 100 mm. To simulate the non-linear and time-dependent behaviour of the shotcrete lining, a shotcrete constitutive model is used which developed and implemented in a numerical software. It is required a number of input parameters, as shown in Table 3, some of these parameters are obtained from the results of shotcrete samples that tested during tunnel construction as shown in Table 2. Tensile strength parameters $f_{t,28}$, $G_{t,28}$ and f_{tun} represent the steel fibre content of 35 Kg/m^3. Other parameters have been assumed base on the recommended values, provided by Schädlich and Schweiger [17], which are obtained based on previously published experimental data of shotcrete and concrete.

Table 2: Site Results of the SFRS Compressive Strength

Age	Compressive strength (MPa)
1 h	1.5
8 h	7.8
1 day	15
3 day	30.7
7 day	3.24
28 day	35

Table 3: Shotcrete Model Input Parameters for the SFRS Lining

Parameter	Explanation	Value	Unit
E_{28}	Young's modulus	28	GPa
ν	Poisson's ratio	0.2	-
$f_{c,28}$	Uniaxial compressive strength at t_{hyd}	35 (UCS test)	MPa
$f_{t,28}$	Uniaxial Tensile strength at t_{hyd}	2.5 (4-point bend beam test)	MPa
ψ	Dilatancy Angle	0	Deg
$\varphi_{\max.}$	Maximum friction angle	37	Deg
E_1 / E_{28}	Time dependency of elastic stiffness	0.65	--
$f_{c,1} / f_{c,28}$	Time dependency of strength	-2 (class J2) [13]	--
f_{con}	Normalized initially mobilised strength	0.15	--
f_{cfn}	Normalized failure strength	0.1	--
f_{cun}	Normalized residual strength	0.1	--
$G_{c,28}$	Compressive fracture energy shotcrete	70	KN/m
f_{tun}	Ratio of residual vs. Peak tensile strength	0.1	--
$G_{t,28}$	Tensile fracture energy of shotcrete	2.72 (Acc. to Barros andFigueiras [21]	KN/m
ε_{cp}^{p}	Uniaxial plastic failure strain at 1h, 8h, and 24h	1h= -0.03, 8h= -0.001, after 24h= -0.0007 [17]	--
φ^{cr}	Ratio between creep & elastic strain	2.6	%
t_{50}^{cr}	Time for 50% of creep strain	1.5	D
$\varepsilon_{\infty}^{shr}$	Final shrinkage strain	-0.0005	%
t_{50}^{shr}	Time for 50% of shrinkage strain	45	D
t_{hyd}	Time for full hydration	28	d

5. Results and discussion

5.1. Shotcrete model validation

To validate the shotcrete constitutive model, the laboratory results presented by Al-Ameeri [22] are back-analysed using the shotcrete model. Different steel fibre contents have been used to investigate the fresh and hardening properties of steel fibre self compacting concrete (SCC). The back-analysis focusses on the development of the concrete compressive strength for SF1, SF2 and SF3 mixtures at 7, 28 and 90 days. The steel fibre content for SF1, SF2 and SF3 mixes are 0%, 0.5% and 0.75% by volume of the total mixture, respectively. The input parameters of shotcrete model for these mixes are shown in Table 4. The values of the elastic stiffness E_{28}, compressive strength $f_{c,28}$, tensile strength $f_{t,28}$ and steel fibre content of the concrete mixes are determined based on the experimental data. The comparison between the shotcrete model results and the laboratory results is present in Fig. 5, in which the development of the concrete compressive strength with time is evaluated. The results indicate a good agreement between the shotcrete model results and laboratory results. The results also demonstrate the ability of the shotcrete model to predict the compressive strength of concrete at the period between 7 and 28 days. As a matter of fact, the shotcrete model accounts only for 28 days. According to Schütz [6], no additional development can occur in material properties after 28 days for numerical analysis of hardened shotcrete, therefore:

- Shotcrete age ≤ 28 days → Changing material properties
- Shotcrete age > 28 days → Constant material properties

Table 4: Input Parameters of the Shotcrete Model of the Concrete Lining

Parameter	Value			Remarks	Unit
	SF1	SF2	SF3		
E_{28}	24.5	26	27.2	Lab data [22]	GPa
ν	0.2				-
$f_{c,28}$	35.4	37.6	45.2	Lab data [22]	MPa
$f_{t,28}$	5.5	7.5	8.5	Lab data [22]	MPa
ψ	0				Deg
$\varphi_{\max.}$	37				Deg
E_1 / E_{28}	0.6				--
$f_{c,1} / f_{c,28}$	0.4			CEB-FIP model [12]	--
f_{con}	0.15				--
f_{cfn}	0.1				--
f_{cun}	0.1				--
$G_{c,28}$	70				KN/m
f_{tun}	0				--
$G_{t,28}$	0.1	3.38	6.9	Acc. to Barros and Figueiras [21]	KN/m
ε_{cp}^{p}	1h= -0.03, 8h= -0.001, after 24h= -0.0007				--
φ^{cr}	2.5			Eurocode 2 [15]	%
t_{50}^{cr}	1.5				D
$\varepsilon_{\infty}^{shr}$	-0.0005				%
t_{50}^{shr}	45				D
t_{hyd}	28				d

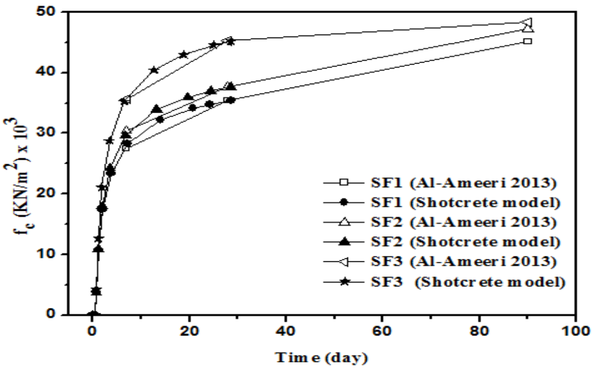


Fig. 5: Shotcrete Model Validation for Concrete Compressive Strength Development with Time.

5.2. Parametric study

To investigate the influence of the shotcrete model parameters on the time-dependent behaviour of the shotcrete lining, a parametric study is performed. It involves deactivating the model features separately and evaluate their effect on the development of the shotcrete lining stiffness, strength, stress, and displacement with time. For the current project, the stresses at the crown and toe of the tunnel lining are compression stress while the sidewalls are undergoing tensile stresses, as shown in Fig. 6. The development of the major stresses and vertical displacement in four different point along the tunnel lining with time is evaluated is (see Figures 7). It's obvious that the compression stresses at the sidewalls of the tunnel are higher than the tensile stresses at the crown and toe. The displacement at the tunnel crown and toe is higher than that at the sidewalls. In another word, the vertical displacement of the shotcrete lining is more in tension than in compression. In addition, the stresses and displacement in the tunnel lining are approximately symmetric around the y-axis so that the analysis of one half of the tunnel lining is considered for the parametric study.

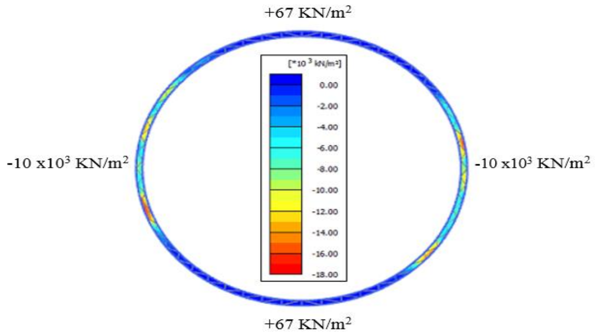
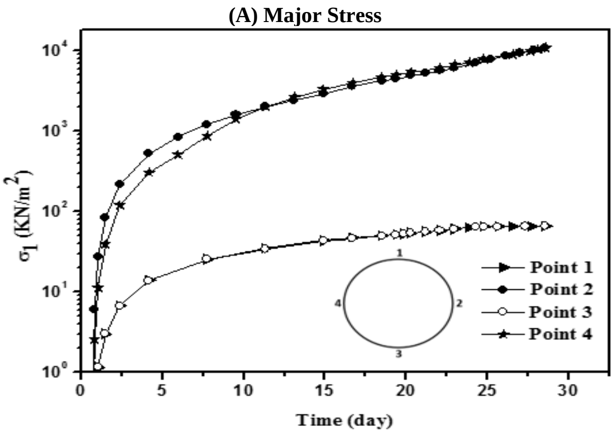


Fig. 6: Principal Compression and Tensile Stresses along the Tunnel Lining.



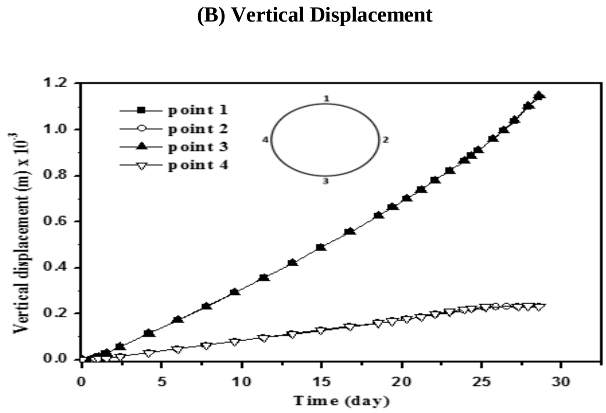


Fig. 7: Develpoment of the Stress and Vertical Displacement around the Tunnel Lining With Time.

5.2.1. Time-dependent strength parameter

In the shotcrete model, the early compressive strength of the shotcrete lining f_c can be assumed based on the early strength classes J1, J2 and J 3 which refer to shotcrete strength at different ages up to 24 hours, as presented by EN 14487-1. The shotcrete classes are the input values for the time dependency of strength $f_{c,1}/f_{c,28}$.The input values of J1, J2 and J3 are -1, -2 and -3, respectively [17]. The shotcrete strength class used in the field is class J2. The evaluation of $f_{c,28}$, based on the shotcrete strength classes with time, compared with the compressive strength of shotcrete samples made during tunnel construction, as shown in Fig. 8. The shotcrete class J3 produces a higher compressive strength compared to that obtained during tunnel construction while class J1 gives a lower value of the compressive strength. The result of shotcrete class J2 is in between the two classes and shows better agreement with the field results of shotcrete compressive strength. Generally, the curves predict a sharp increase in the compressive strength for the early days after shotcrete application, by increasing the time it becomes less pronounced until it attends the final strength of hardening shotcrete.

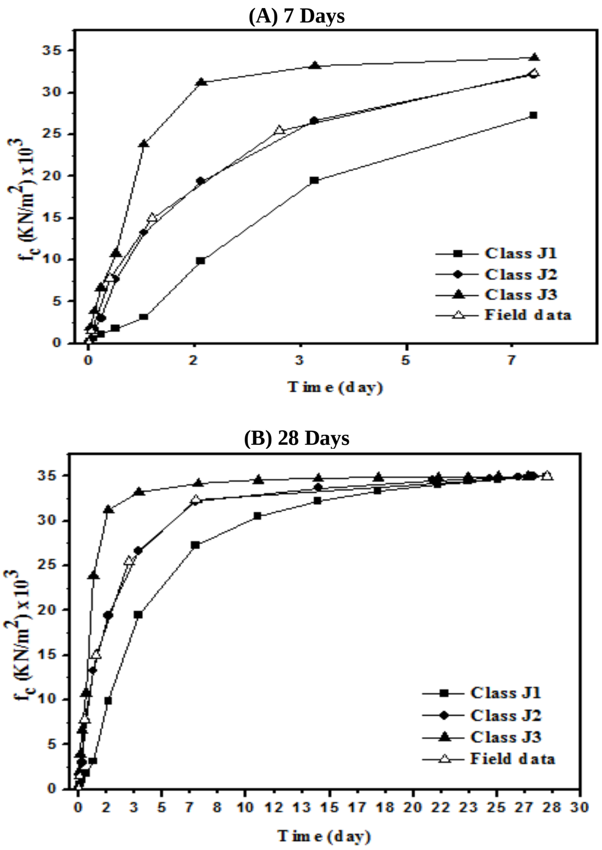


Fig. 8: Evaluation of Shotcrete Strength Classes with Time for A) 7 Days, B) 28 Days.

5.2.2. Time-dependent stiffness parameter

According to the cement hydration past, the shotcrete stiffness is increased immediately with time. The development of shotcrete stiffness with time, in the shotcrete model, is following the recommendation of CEB-FIP model code [12] as shown in Eq. (2). The stiffness ratio E_1/E_{28} is the parameter that represents the time dependency of the shotcrete elastic stiffness. In this section, different values of the stiffness ratio are used to investigate its impact on the development of shotcrete stiffness with time. The values are selected according to the recommended values provided by Schädlich and Schweiger [17]. Figure 9 presents the development of the shotcrete stiffness in 7 days and 28 days using four values of the stiffness ratio E_1/E_{28}, respectively. Increasing the stiffness ratio can increase the shotcrete stiffness with time. This increase is clearly visible in the early days of application, particularly in the range of 1h ≤ t ≤ 20 days. Similar to the increase of the compressive strength with time, the curves of the elastic stiffness with time predict a sharp increase for the first day of application. By increasing the time, the rate of increase becomes less.

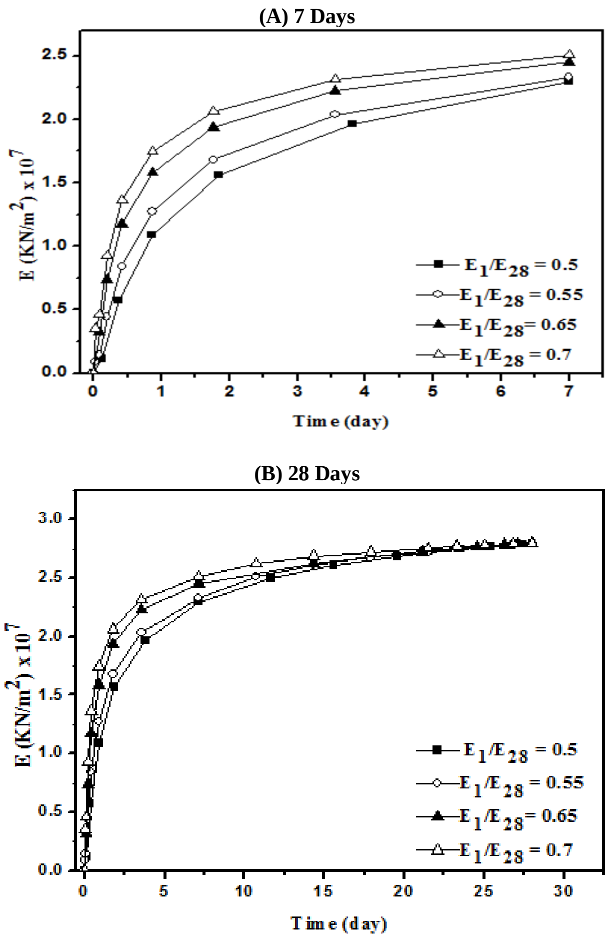


Fig. 9: Shotcrete Elastic Stiffness with Time in A) 7 Days, B) 28 Days.

5.2.3. Effect of creep and shrinkage

Creep and shrinkage are physical properties of concrete. Creep is known as the elastic and long-term deformation of concrete under a continuous load. Whereas the shrinkage of concrete is defined as the volumetric changes of concrete structures due to the loss of moisture by evaporation. It is a time-dependent deformation that decreases the concrete volume without any external loads. In this section, the influence of creep and shrinkage strain on the time-dependent behaviour of the steel reinforced shotcrete lining is evaluated since these two phenomena are considered in the shotcrete model. The effect of creep and shrinkage strain is represented by the creep factor φ^{cr}, shrinkage strain $\varepsilon_{\infty}^{shr}$, time for 50% of creep strain t_{50}^{cr} and time for 50% of shrinkage strain t_{50}^{shr}, as presented in Table 3. The effect of these two phenomena is considered in two cases; without creep and shrinkage effect and with creep and shrinkage effect. Figure 10 shows the effect of creep and shrinkage strain on the development of the shotcrete lining stresses with time. Activation of creep and shrinkage strain shows a reduction in the development of the lining compression and tensile stresses with time. The reduction in the development of the lining stresses with time starts from the early days of application.

The effect of creep and shrinkage strain on the development of the vertical displacement of the shotcrete lining with time is shown in Fig. 11. The creep and shrinkage strain have a less effect in the development of the vertical displacement with time, at the tunnel crown. However, the development of the vertical displacement with time at the tunnel sidewall increases by activating of the creep and shrinkage.

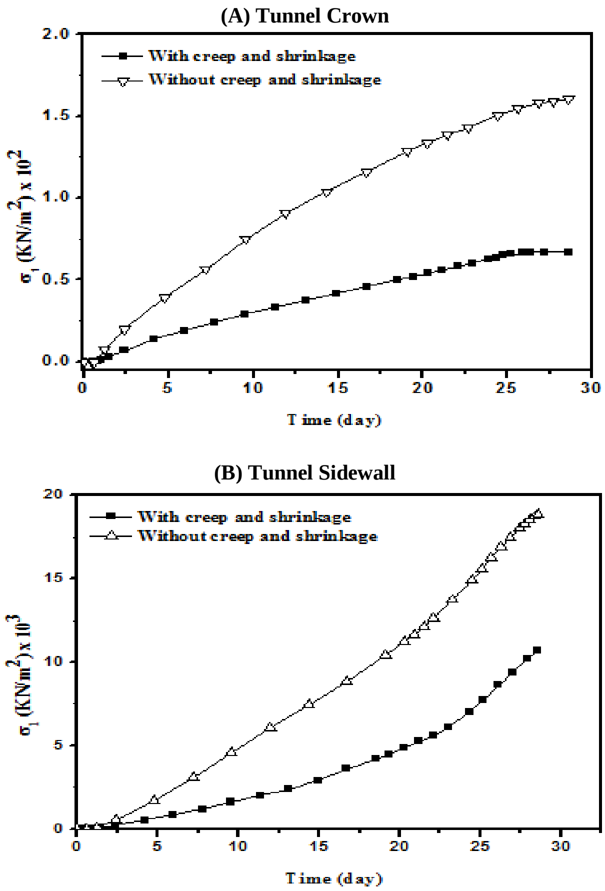
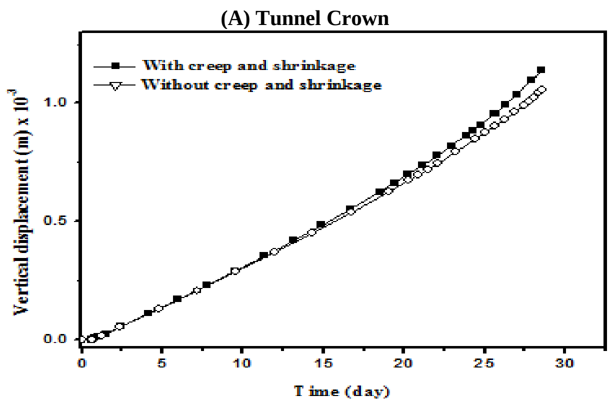


Fig. 10: Effect of Creep and Shrinkage Strain on Development of Shotcrete Stress with Time.



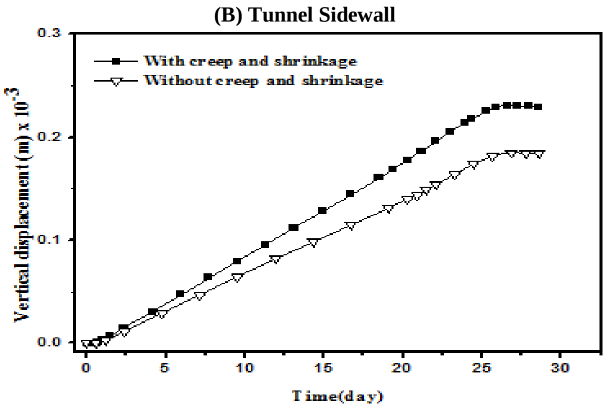


Fig. 11: Effect of Creep and Shrinkage Strain on Development of Lining Displacement with Time.

5.2.4. Steel fibre effect

The effect of steel fibre on the development of tunnel lining behaviour with time is predicted. The input parameters of the unreinforced tunnel lining based on the shotcrete model are listed in Table 5. The results of unreinforced tunnel lining are compared with that of reinforced tunnel lining. The input parameters of the reinforced tunnel lining are listed in Table 3. Figure 12 shows the development of compressive strength and elastic stiffness of the reinforced and unreinforced tunnel lining with time, respectively. Due to higher compressive strength and elastic stiffness of the reinforced tunnel lining, the development of its compressive strength and elastic stiffness with time is higher than that of the unreinforced tunnel lining.

Table 5: Shotcrete Model Parameters for the Unreinforced Tunnel Lining

Parameter	Value	Remarks	Unit
E_{28}	25.33	Acc. EN 1992-1-1	GPa
ν	0.2		-
$f_{c,28}$	16	f_{ck} of (C16/C20)	MPa
$f_{t,28}$	0		
ψ	0		Deg
$\varphi_{\max.}$	37		Deg
E_1 / E_{28}	0.5	Schädlich and Schweiger (2014 b)	--
$f_{c,1} / f_{c,28}$	0.4	(CEB-FIP model)	--
f_{con}	0.15		--
f_{cfn}	0.1		--
f_{cun}	0.1		--
$G_{c,28}$	70		KN/m
f_{tun}	0		--
$G_{t,28}$	0.1	According to Barros & Figueiras 1999	KN/m
ε_{cp}^{p}	1h= -0.03, 8h= -0.001, after 24h= -0.0007	Schädlich and Schweiger (2014 b)	--
φ^{cr}	2.5	(Eurocode 2)	%
t_{50}^{cr}	1.5		D
$\varepsilon_{\infty}^{shr}$	-0.0005		%
t_{50}^{shr}	45		D
t_{hyd}	28		d

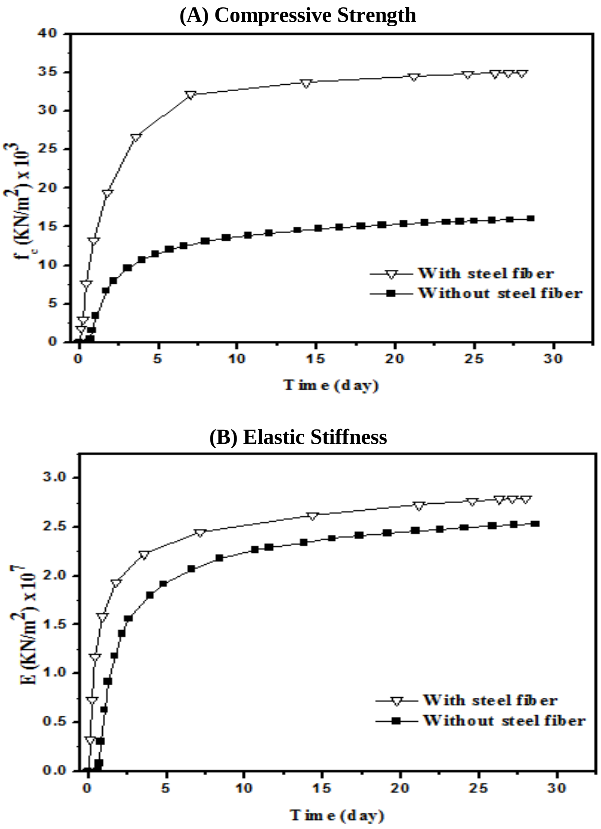
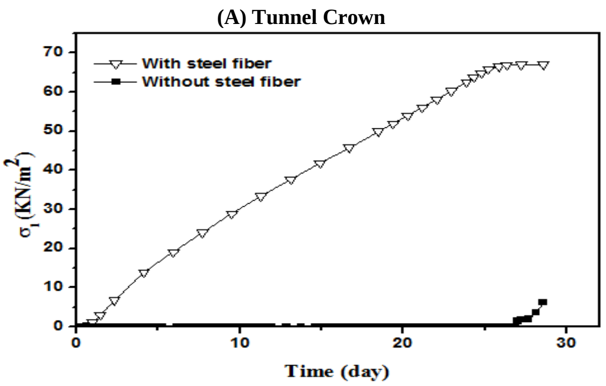


Fig. 12: Development of Compressive Strength and Elastic Stiffness of Reinforced and Unreinforced Tunnel Lining with Time.

The effect of the steel fibre on the development of lining stresses is shown in Fig. 13. The result indicates that the absence of the steel fibre causes a significant effect on the development of the tunnel lining stresses with time. The greatest effect of the steel fibre is more obvious in reducing the lining tensile stresses at tunnel crown (see Figure 13a). The development of the lining compression stresses at the tunnel sidewalls starts to decrease in the latter days of application, as shown in Fig 13 b. In addition, the stress-strain curve of the reinforced and unreinforced tunnel lining is shown in Fig. 14. The stress-strain curve of the reinforced tunnel lining is higher than that of unreinforced tunnel lining. As mentioned previously, the stress are tunnel crown and toe are compression stresses while sidewalls are undergoing tensile stresses. Generally, the concrete is weak in tension and the addition of steel fibre can improve its ability to withstand impact loads. Thus, the largest decrease in the shotcrete stress, due to the absence of steel fibre, is observed in the tunnel crown. The increase of the vertical displacement with time in cases of the reinforced and unreinforced tunnel lining is shown in Fig. 15. It is clear that the development of the vertical displacement with time is not affected by the addition of steel fibre.



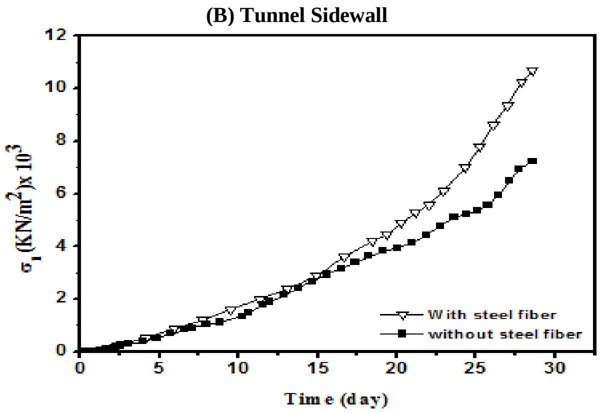


Fig. 13: Effect of Steel Fibre Content on the Development of Lining Stress with Time.

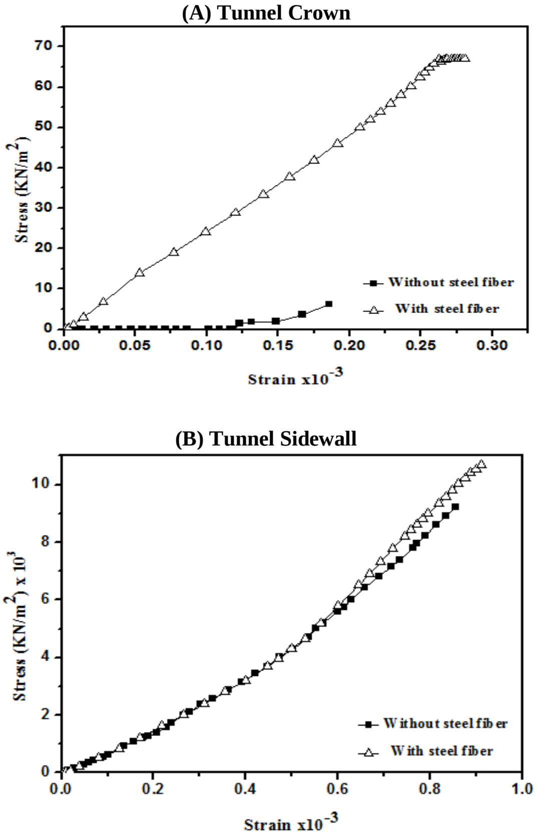
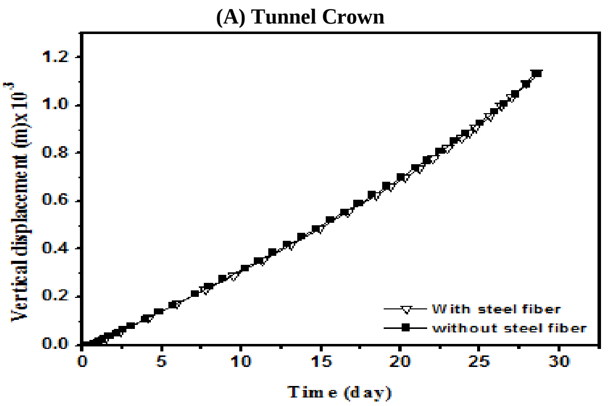


Fig. 14: Stress-Strain Curve of the Reinforced and Unreinforced Tunnel Lining.



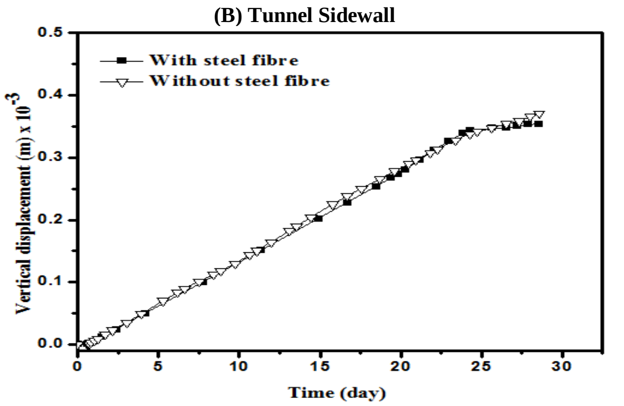
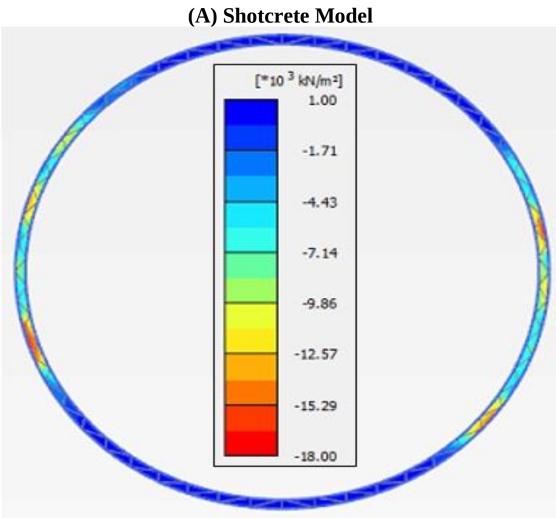


Fig. 15: Effect of Steel Fibre Content on the Development of Lining Displacement with Time.

5.3. Linear and non-linear behaviour of the shotcrete lining

In a conventional numerical analysis, the shotcrete behaviour is simulated using a simple material method such as linear-elastic models while the shotcrete model represents the shotcrete lining as a highly non-linear behaviour. In this work, the steel fibre reinforced shotcrete lining is analysed using the shotcrete model, with all its features, and an elastic analysis model. A constant young modulus of 28 GPa is assumed for the elastic analysis. The results of the elastic analysis are compared with that obtained from the constitutive shotcrete model. The distribution of the lining stresses along the tunnel lining using the shotcrete model and the elastic analysis is shown in Fig. 16. The SFRS lining stresses along the tunnel circumference starting from the tunnel crown for the two cases is presented in Fig. 17. The major principal stress in case of elastic analysis is higher than that obtained using the shotcrete model. The largest differences in stress between the two cases are observed along the tunnel side walls. The vertical displacement along the tunnel lining is investigated using the two cases as shown in Fig. 18, in which the elastic analysis with a constant young modulus decreases the displacement comparing with the vertical displacement resulted from the shotcrete model. However, the difference in the vertical displacement gained from the two cases is not very significant.



(B) Elastic Analysis

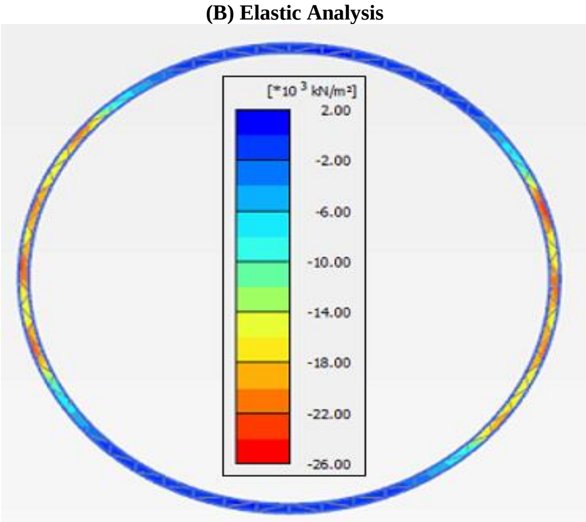


Fig. 16: Distribution of Major Principal Stress of the Tunnel Lining Using (A) Shotcrete Model and (B) Elastic Analysis.

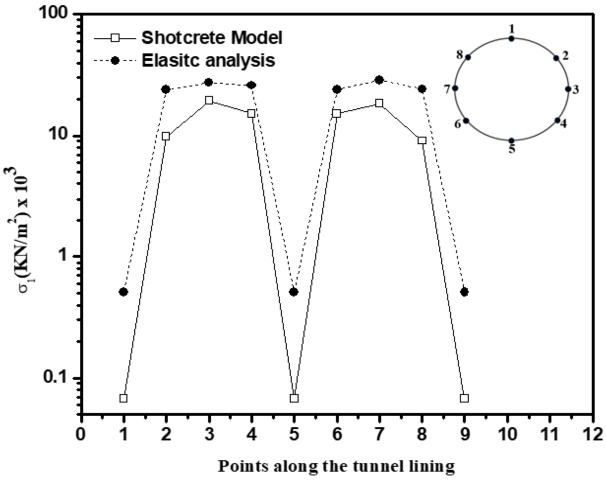


Fig. 17: Major Principal Stress along the Tunnel Lining Using the Shotcrete Model and the Elastic Analysis.

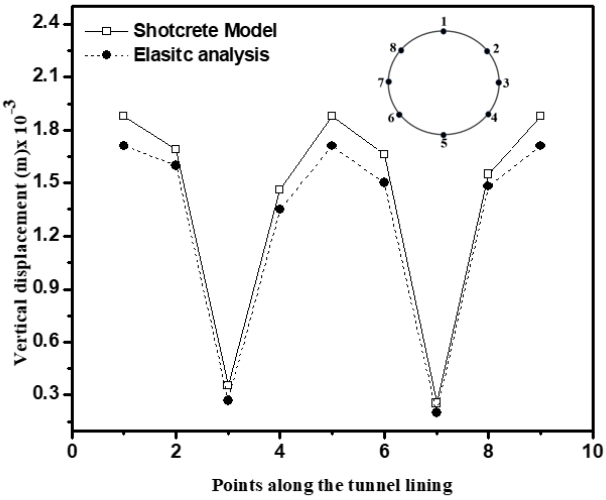


Fig. 18: Vertical Displacement along the Tunnel Lining Using the Shotcrete Model and the Elastic Analysis.

6. Conclusion

In this paper, a shotcrete constitutive model is applied to examined the influence of some model input parameters on the shotcrete time-dependent behaviour. Shotcrete model is based on Elasto-plastic strain hardening/softening plasticity and can be used for any cement-based materials such as shotcrete, cast concrete, jet grout etc. It has the ability to consider the loading history, cracking, time-dependent behaviour and non-linearity of any cemented material. The geometry and geology of the case study are taken from Pahang-Selangor Raw Water Transfer Project. Based on the results, high compression stresses have resulted at the tunnel sidewalls while lower tensile stresses observed at the crown and toe. The shotcrete lining displacement in the tunnel crown is higher than that at its sidewalls. The model parameters that studied in the analysis are the time-dependent stiffness/strength parameters, creep and shrinkage parameters and steel fibre parameters. A parametric study is performed by deactivating these parameters separately and investigate their effect on the development of shotcrete stiffness, strength, stress, and displacement with time. The results indicated that the variation of the shotcrete strength classes has a noticeable influence on the development of shotcrete compressive strength with time, particularly during the first days of application. Comparing with the shotcrete compressive strength obtained during tunnel construction, shotcrete class J3 results in higher compressive strength while class J1 decreases the early compressive strength with time. Among the shotcrete strength classes, class J2 shows good agreement with the field compressive strength. The effect of stiffness ratio on the development of SFRS lining stiffness with time is evaluated. The higher stiffness ratio increases the shotcrete stiffness, especially after a few days of application. The effect of shotcrete creep and shrinkage strain on the development of shotcrete stress and displacement with time is evaluated. Activation of creep and shrinkage strain shows a visible reduction in the development of the shotcrete lining stresses with time. The effect of steel fibre on the time-dependent behaviour of the shotcrete lining is predicted. For reinforced tunnel lining, the development of the compressive strength and elastic stiffness with time is higher than that of the unreinforced tunnel lining. The absence of steel fibre caused a largest decrease in the lining tensile stress in the tunnel crown while the development of lining compression stresses with time, at the tunnel sidewalls, starts to decrease in the latter days of application. This is so because concrete is weak in tension and adding the steel fibre can improve its ability to withstand impact loads. Finally, the tunnel lining behaviour is analysed using shotcrete model and the elastic analysis to show the difference between these two approaches and identify their impact on the lining behaviour. The elastic analysis, with a constant young modulus of elasticity of 28 MPa, showed a significant increase in the tunnel lining stresses as compared with that obtained using shotcrete model. These results confirm the shotcrete model's ability in producing a reasonable result for the design requirement.

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