Analysis of Interaction Behaviors between Rock and Early-age Shotcrete Liner with High Strength

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***Abstract*—This study introduced a sprayed concrete with early-age and high compressive strength characteristics for ground stabilization and analyzed the interaction behaviors between the shotcrete and rock mass. A modeling technique for simulating time-dependent behaviors of the shotcrete such as early age hardening was proposed and was verified by comparing an analytical solution from the convergence-confinement method for tunnel support design. Using a practical example of tunneling, it was shown that detailed subdivision description of hardening process was necessary to predict reasonable responses of a sprayed concrete liner, especially for the early-age sprayed concrete.**

***Keywords*— Sprayed Concrete, Hardening, Soil-Structure Interaction, Convergence-Confinement Method, Time Dependent**

I. INTRODUCTION

With increasing transportation volume and growing population, development of underground space has been needed. In particular, underground structure construction in an urban area causes increase of socio-economic costs, thus they have to be rapidly constructed to stabilize the ground. NATM tunneling is a conventional ground excavation method that sprayed concrete is lined on the excavation surface to control ground deformation. The deformation is confined by hardening sprayed concrete (shotcrete); the ground-linear interaction is effected by time-dependent material properties of shotcrete such as deformable modulus and strength, consequently changes in these parameters should be considered.

An early-age shotcrete with high strength would be one of the most proper material to apply into tunnel excavation because the material makes possible to reduce the use of steel supports and to increase excavation length per day. It also requires less amount of shotcrete materials to support surrounding ground, thereby reducing construction cost and improving workability. The early-age shotcrete has been applied to tunneling in Japan and Europe, and as a result, several tunnels were constructed without steel supports or with thin thickness of liner [1].

Although there are several studies [1, 2, 3] on the interaction between ground and tunnel support, linear elastic model for shotcrete was used; subsequent studies [4, 5] were also conducted, but they simply provided advanced analytical models including elastoplastic behaviors of ground. Furthermore, in conventional NATM tunnel lining design, the description of shotcrete hardening is divided into two stages: initial and complete hardening states. However, this conventional approach considers changes in material properties of shotcrete roughly, and a structural analysis using them can result in improper stresses and deformation of tunnel. For this reason, several studies on the interaction between ground and tunnel lining, considering time-dependent behaviors of shotcrete, have been conducted by other researchers. Pan and Dong [6] proposed a tunnel model based on viscoelastic theory to represent tunnel deformation and conducted parametric analyses to investigate effects of excavation and support installation. Oreste [7] presented an analytical model that can consider not only time-dependent elastic modulus and strength of shotcrete but also excavation length and rate. Cho et al. [8] analyzed the interaction between rock and deteriorated supports over time changes.

Early aged shotcrete has high strength and elastic modulus at the initial hardening state. With respect to the interaction between ground and structures, applying the material to tunnel liner would show different interaction behaviors from that of general shotcrete. However, previous studies were restricted to the interaction related to general shotcrete. For the above reason, this study analyzed the interaction between rock and tunnel liner made of an early-age shotcrete. First, the convergence-confinement method using the analytical model by Oreste [7] was applied for tunnel analysis to investigate the behavior of the early aged shotcrete. In addition to the analytical model, three dimensional nonlinear finite element model was simulated to analyze differences between the two models due to excavation.

II. METHODS

A. Early-age strength of shotcrete

For an early-age shotcrete, an alkali-free accelerator, which is a power type mainly composed of $C_{12}A_7$ unlike a conventional alkali free accelerator and contains alkali less than 1%, was added to the shotcrete to expedite hardening. Using the accelerator enables the mixture design of shotcrete to enhance its strength without the use of silica fume; As a result, construction cost can be reduced by 10% of the expected cost. The shotcrete is designed to have the compressive strength of 45 MPa. Generally, cement-based materials with high strength is stiffer than that with normal strength. Because a tunnel liner interacts with surrounding ground, a shotcrete stiffness increase causes change in the interaction behavior between the shotcrete and the ground; the deformation characteristics of the shotcrete rapidly changes as it hardens, and the interaction between the shotcrete and the excavation surface of the ground changes as a result.

With respect to design and numerical analysis, the estimation on changes in strength and deformation of the shotcrete is very important. However, until now there has been no typical procedure for the estimation [9, 10]. In this study, analytical formulae for strength and elastic modulus of the shotcrete as a function of time were used. To determine reasonable fitting parameters, pin test, pullout test, and uni-axial compressive test (UCT) of the shotcrete were conducted; there were measurement limits of each test method for estimating the strength. Two types of shotcrete mixture were designed as shown in Table 1. They were identical to each other except the amount of accelerator and early-age admixture used. From the tests, the compressive strength of the early-age shotcrete specimens was determined as shown in Table 2. For pin test, compressive strength of shotcrete could not be estimated because shotcrete was too weak to measure the penetration depth of pin.

B. *Convergence-confinement method*

Although a three dimensional finite element method is a powerful tool to simulate tunnel excavation and to reproduce liner installation and hardening states at each construction stage, it requires large amount of computational costs, and the model can be improper to design support members of a tunnel. For this reason, the convergence-confinement method (CCM), consisting of ground reaction and liner supporting curves, has been widely used in a practical design. The model is based on two-dimensional plane strain condition, and uses a load distribution ratio for ground due to excavation, to consider three dimensional behaviors such as a longitudinal arching effect; the ratio means actual ground load, which is reduced by the arching.

Even though the method can be only applied to a circular tunnel within isotropic and homogenous ground with the initial lateral coefficient of 1.0, it is beneficial to explain clear relationship between material characteristics and behaviors of the support and ground, and to provide ground pressure on the shotcrete liner and the displacement at the time when the ground deformation is completely converged. After the method was proposed by Fenner [11], it has been expanded into the model that can reproduce time-dependent behavior of shotcrete support and elasto-plastic behaviors of ground.

The ground reaction curve was derived based on elasticity and Mohr-Coulomb plasticity theory with a non-associated flow rule. First, solution of the problem on an infinite media with a circular hole was used for linear elastic region of the ground. After plastic behaviors of the ground, the elasto-plastic solution was used for ground near the hole while the linear elastic solution is applied to far-field region as shown in Figure 1. Each notation in Figure 1 is as follows: a, radius of tunnel; r, distance between a point within ground media and the center of tunnel; R, radius of plastic region; p_i, internal pressure on the inner surface; p_o, geostatic pressure. To represent brittle behavior of weathered rock, residual shear parameters were applied to the plastic solution after yielding. Detailed derivation of the solutions can be referred to other literature [12].

TABLE I. MIXTURE DESIGN

Mixture detail	Mixture Type	
	I	II
Gmax (Mm)	13	13
W/C (%)	40	40
S/a (%)	60	60
Water content (kg/m^3)	192	192
Coarse aggregate (kg/m^3)	619	619
Fine aggregate (kg/m^3)	988	988
Superplasticizer (%)	1	1
Accelerator (%)	5	10
Early-age admixture (%)	5	10
Steel fiber (%)	40	40

TABLE II. CHANGE IN COMPRESSIVE STRENGTH

Time (hr.)	Compressive strength (MPa)		Test type
	I	II	
1	-	1.7	Pullout
3	1.5	2.3	Pullout
18	8.0	11.8	Pin
26	13.4	21.0	Pin
72	27.0	32.5	UCT
168	36.6	42.3	UCT
672	42.0	48.0	UCT

A time-dependent shotcrete constitutive model was used to create the support characteristic curve, representing rapid hardening process of the early-age shotcrete. For deformable modulus and strength of the shotcrete, formulae that had been proposed by Pöttler [13] and Weber [14] were used, respectively.

$$E_s=E_{s,0}\,(1-\exp(-\alpha t)) \quad (1)$$

$$\sigma_c=\sigma_{c,0}\,(1-\exp(-\beta t)) \quad (2)$$

In equations (1) and (2), each notation is as follows: E_s, deformable modulus of shotcrete at time t; $E_{s,0}$, E_s at time 0; σ_c, compressive strength of shotcrete at time t; $\sigma_{c,0}$, σ_c at time 0; t, current time; α and β, hardening parameters. Applying results from the compression tests to equation (1), hardening parameter α was determined by regression analysis. The initial elastic modulus was estimated based on the initial compressive strength, and α and β were assumed to be the same. From the regression analysis using experiment results, which are from the field test at the JinJu-Kwangyang tunnel in Korea, hardening parameters were determined as 0.013, as shown in Figure 2. To highlight its behaviors, the same work was also conducted for normal shotcrete with the compressive strength of 21 MPa; the hardening parameters were estimated as 0.008.

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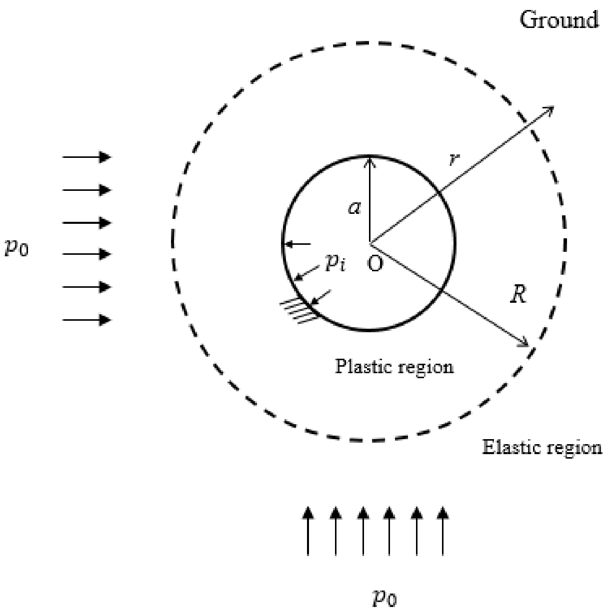


Figure 1 Scheme of circular tunnel embedded in elastoplastic media under hydrostatic pressure

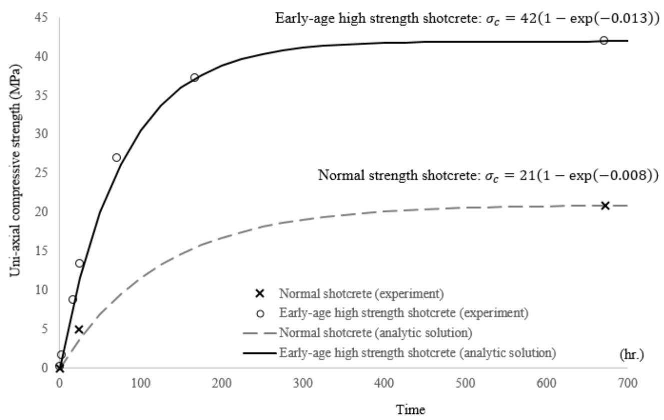


Figure 2 Change in compressive strength of shotcrete and estimation of hardening parameters

C. *Procedure for time-dependent support curve*

Shapes of support characteristic curves in preliminary tunnel design are linear because real factors such as time-dependent hardening of shotcrete and dead time due to installation are not considered. The use of the linear curve causes underestimation of shotcrete liner deformation. To apply a nonlinear support characteristic curve to the confinement-convergence analysis, Oreste (2003)'s analytical method [7] was used. In this paper, the procedure for making the curve is briefly described.

- Using the deformable modulus of the shotcrete at time j-1, stiffness ratio for circular tunnel is estimated using the following equation.

$$k_{j-1} = \{ a^2-(a-t_{sh})^2)E_{sh,j-1} \} / \{ a(1+\nu)(1-2\nu_{sh})a^2+(a-t_{sh})^2) \} \quad (3)$$

where E_{sh}: Deformable modulus of shotcrete, ν_{sh}: Poisson's ratio of shotcrete, t_{sh}: thickness of shotcrete liner. Equation (1) is used to calculate E_{sh}.

- In the second step, a pressure on the outer surface of the liner was determined by the following equation:

$$P_{lin,j}=\Sigma(k_{n-1}\,\Delta u_n) \; (n=1,2,\ldots, j) \quad (4)$$

where $P_{lin,j}$: the pressure on the liner at step j, k: stiffness of shotcrete, Δu: displacement increment at step j. Although formula (3) is expressed explicitly, the support pressure is discretely and implicitly determined because the stiffness is nonlinear.

- Using the current displacement u_j, earth pressure is estimated from the ground reaction curve, and then fictitious support pressure that resulted from the arching effect is calculated. Oreste (2003) considered disappearance of the fictitious pressure, which was estimated using the formula proposed by Panet and Guenot (1982), due to increase excavation length. This study adopted the same method. Detailed equations can be referred in Oreste (2003) and key equations is listed as follows:

$$u_j=u_{j-1}+\Delta u_j \quad (5)$$

$$P_{g,j}=g(u_j) \quad (6)$$

$$P_{fict,j}=P_{g,j}-P_{lin,j} \quad (7)$$

where u: total convergence displacement, g: ground reaction function, P_g: earth pressure, P_{fict}: fictitious support pressure.

- Finally, the maximum tangential stress of the shotcrete support exerted by P_{lin} is calculated as follows:

$$\sigma_{max,j} = c\,\Sigma(E_{shot,n-1}\,\Delta u_n) \quad (n=1,2,\ldots, j) \quad (8)$$

where c: $2a / (1+\nu_{shot})/(a-t_{sh})^2+(1-2\nu_{shot})a^2)$. The stress is compared with the uni-axial strength of the shotcrete, and consequently is used to calculate the safety factor of the shotcrete liner during hardening. Because the shotcrete support curve is for the external radial pressure on the surface of the liner, the pressure increment, corresponding to the maximum tangential stress and the strength of shotcrete, has to be expressed as follows:

$$\Delta P_j = 0.5\,(1 - (a - t_{sh})^2 / a^2)\,(\sigma_{c,j} - \sigma_{max,j}) \quad (9)$$

The support pressure is finally calculated by the following equation:

$$P_{c,j}=P_{lin,j}+\Delta P_j \quad (10)$$

D. *Finite element model*

A finite element model was also created to represent time dependent interaction behavior between the shotcrete liner and ground; this model was used to estimate the analytical solution proposed by Oreste (2003) and to apply to a practical tunnel under construction, not limited to circular tunnel which is loaded by geostatic earth pressure with the lateral earth pressure coefficient of 1.0. To reproduce time dependent characteristic of the liner, the model considered construction steps and changes in material properties. During excavation and installation, the transition from softening to hardening was modeled by using discrete changes in deformable modulus and strength of the shotcrete for 8 phases. Furthermore, a model considering the hardening process for 2 phases (softening and hardening) was generated to analyze effects of subdivision level for hardening on the interaction between the liner and the ground.

The commercial finite element analysis program Midas GTS was used to simulate tunnel excavation, liner installation, and change in material properties. For ground, Mohr-Coulomb plasticity model was applied to predict the earth pressure and the deformation. However, because the used program can reproduce the multi-linear constitutive relation for deformable modulus, changes in the strength of the shotcrete liner was excluded in the model.

III. NUMERICAL EXAMPLE: CIRCULAR TUNNEL

CCM was used to find the support pressure and convergence displacement of a circular tunnel embedded in elastoplastic media. A finite element model that has the same ground and support conditions with those of the analytical model was also generated.

To compare with results from CCM and a finite element model, the lateral earth pressure coefficient was assumed to be 1.0; this means a hydrostatic pressure was applied on the exterior surface of the liner. Complex hardening behaviors of the early age high strength of shotcrete was simplified as a function of the deformable modulus only; it was assumed to change from 16 to 31 GPa (Table 3), and other material parameters of the shotcrete was assigned as follows: Poisson's ratio of 0.2 and unit weight of 24 kN/m^3. For ground, material properties are listed in Table 4. In Tables 3 and 4, each notation indicates as follows: t: time, E: deformable modulus, γ: unit weight, ϕ: internal friction angle, c: cohesion strength. In CCM, the time when the shotcrete liner is installed is important for determining the support pressure at the equilibrium because it is related to fictitious earth pressure due to arching effect. In this example, it was assumed that the shotcrete liner was installed when the ground relaxed to 72% rather than the initial geostatic state; the ground opening contraction was thus 2.188 mm.

Comparison with the nonlinear support characteristic curves from CCM and a three-dimensional finite element model was conducted. In Figure 3, the curve from the finite element model agrees with that from CCM. However, as the convergence displacement increases, this agreement disappears; the slope of the curve from the finite element model decreases, while that from CCM continuously increases. In a strict sense, it would be due to the fact that the interaction between ground and shotcrete liner is not considered in CCM. Although ground reaction is calculated considering the fictitious support pressure, from the fact that CCM considering time-dependent behaviors of the shotcrete does not require the convergence criteria for iteration, the procedure is straightforward and change in ground deformation due to the liner does not give feedback to calculation of stresses in the support. Nevertheless, the nonlinear curve from CCM can predict the support behavior with low computational costs, when compared to results from the finite element model. Thus, CCM using an algorithm for calculating the time-dependent support characteristic curve can be useful for preliminary design of NATM tunnels.

TABLE III. CHANGE IN ELASTIC MODULUS OF SHOTCRETE

t (hr.)	24	48	72	96	120	144	168	672
E (GPa)	8.31	14.4	18.8	22.1	24.5	26.2	27.5	31.0

TABLE IV. CONSTITUTIVE MATERIAL PARAMETRES FOR GROUND

Rock type	γ (kN/m^3)	E (GPa)	ν	ϕ (°)	c (MPa)
Weathered rock	25.0	4.4	0.25	40	0.7

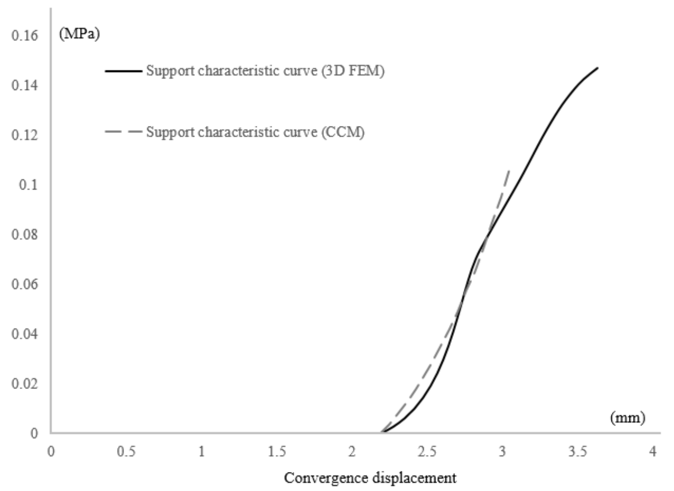
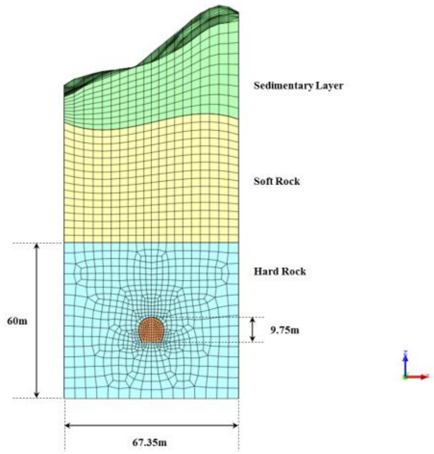


Figure 3 Comparison with results from analytical and numerical models

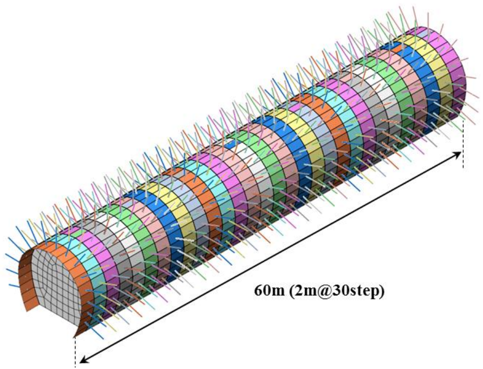
IV. NUMERICAL EXAMPLE: RAILWAY TUNNEL

Although CCM can provide some rough estimation on design loads of the shotcrete liner, its application is restricted to a circular tunnel and the ground with the lateral coefficient of 1.0; a three-dimensional finite element model of rock tunnels is required to predict its mechanical and interaction behaviors under various geostatic conditions.

To analyze effects of segment level of hardening process on the interaction behaviors between liner and surrounding rock, several numerical analyses of a road tunnel with horse-shoe cross section were conducted. This tunnel adopted the early age and high strength shotcrete as a main material of the liner. The liner with the thickness of 80 mm was installed after full cross section excavation with the length of 2.0 m for each step; excavation was conducted for 30 steps. Rock bolts with the diameter of 25 mm and the length of 3.0 m were also installed to reinforce surrounding rock. A numerical model as shown in Figure 4 was created. Solid elements were used to represent soil and rock material parts, while the liner was modeled using shell elements. Material properties are indicated in Table 5. For rock bolts, embedded truss elements were used, and elastic modulus and Poisson's ratio of rock bolts were 210 GPa and 0.3, respectively. Hydraulic conditions were excluded in this model because effects of segment level for hardening process of shotcrete clearly emerged from the analysis. To simulate time-dependent behaviors of the shotcrete, elastic modulus of the shotcrete continuously was changed during excavation; shotcrete hardening was subdivided into eight steps and was described as increase of elastic modulus as shown in Table 3.



(a) Ground layers



(b) Tunnel liner and excavation

Figure 4 Three-dimensional finite element model of tunnel

TABLE V. MATERIAL PARAMETRES OF MULTI-LAYERED GROUND

Rock type	γ (kN/m^3)	E (GPa)	ν	ϕ (°)	c (MPa)
Sedimentary soil	17.5	0.006	0.40	0	0.025
Soft rock	23.0	1.6	0.27	34	0.6
Hard rock	25.0	5.0	0.25	38	1.3

From numerical analysis, it was observed that degree of descriptions for hardening process influences the convergence displacement and support pressure as shown in Figure 5. Curves in Figure 5 were extracted from the liner that was installed after excavating 20 m of singe tunneling. For hardening process description over 2 steps (elastic moduli for soft and hard shotcrete: 16 and 31 GPa, respectively), much larger support pressure was estimated than that for 8 steps. This is due to underestimating the stiffness of the shotcrete liner during initial hardening, in particular for early age and high strength shotcrete. This is explained in detail as follows. When the shotcrete was sprayed on the excavation surface, the ground around a hole to due to excavation had low stiffness if it had been enough relaxed and deformed. Although the shotcrete would become stiffer, the ground load capacity already has reached the peak value and extra earth pressure is then transferred to the liner; the support pressure becomes large. On the other hand, if the shotcrete is rapidly hardened before the ground became enough relaxed to behave plastically, the earth pressure due to the ground relaxation would be small. Considering the mechanism of the ground-liner interaction, lower elastic modulus of the shotcrete, that has just sprayed on, can be applied to numerical models if the 2 step hardening description is used; this results in estimating the lower stiffness of the liner than the actual stiffness because the 2 steps method could not consider its the early age characteristics. Thus, more subdivided hardening process modeling is required to reproduce the interaction between ground and early age shotcrete with high strength.

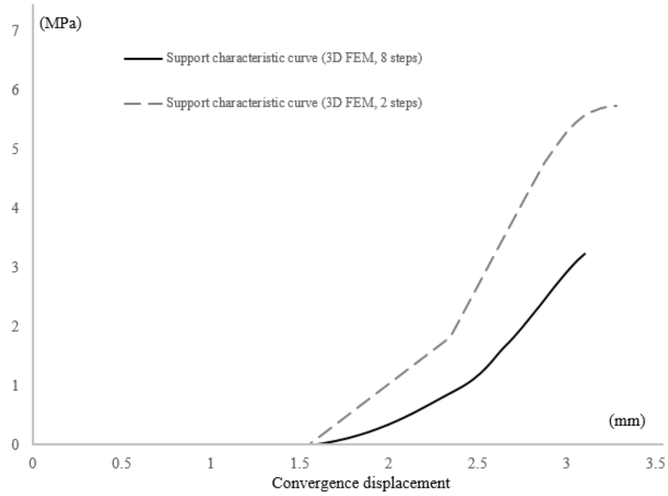


Figure 5 Differences between support characteristic curves due to hardening process subdivision

V. CONCLUSION

This paper presented early-age and high strength shotcrete for ground stabilization after tunneling, and proposed modeling techniques for time-dependent behaviors. The proposed fine subdivision model for shotcrete hardening was verified by comparing an analytical solution from CCM, then was applied to a practical tunneling problem to analyze the interaction behaviors between the shotcrete and the ground. The necessity of the fine subdivision of hardening process for early-age and high strength shotcrete was shown by comparing with results from the rough subdivision model. The rough hardening model overestimated the stiffness and the load capacity of the liner.

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REFERENCES

[1] Brown, E. T., Bray, J. W., Ladanyi, B., and Hoek, E. (1983). Ground response curves for rock tunnels. *Journal of Geotechnical Engineering*, *109*(1), 15-39.

[2] Carranza-Torres, C., and Fairhurst, C. (2000). Application of the convergence-confinement method of tunnel design to rock masses that satisfy the Hoek-Brown failure criterion. *Tunnelling and Underground Space Technology*, *15*(2), 187-213.

[3] Ansell, A. (2007). Dynamic finite element analysis of young shotcrete in rock tunnels. *ACI structural journal*, *104*(1), 84.

[4] Panet, M., and Guenot, A. (1983). Analysis of convergence behind the face of a tunnel: Tunnelling 82, proceedings of the 3rd international symposium, Brighton, 7–11 June 1982, P197–204. Publ London: IMM, 1982. In *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* (Vol. 20, No. 1, p. A16). Pergamon.

[5] Sulem, J., Panet, M., and Guenot, A. (1987). An analytical solution for time-dependent displacements in a circular tunnel. In *International journal of rock mechanics and mining sciences & geomechanics abstracts* (Vol. 24, No. 3, pp. 155-164). Pergamon.

[6] Pan, Y-W., and J-J. Dong. "Time-dependent tunnel convergence—II. Advance rate and tunnel-support interaction." *International journal of rock mechanics and mining sciences & geomechanics abstracts*. Vol. 28. No. 6. Pergamon, 1991.

[7] Oreste, P. P. "A procedure for determining the reaction curve of shotcrete lining considering transient conditions." *Rock Mechanics and Rock Engineering* 36.3 (2003): 209-236.

[8] Jo E.J., Lee, J.S., and Moon, H.K. (2007), Analysis of tunnel behavior due to the deterioration of shotcrete lining using rock-support interaction model, Journal of the Korean Society of Mineral and Energy Resources Engineers, 44(1), 53-60. (In Korean)

[9] Prudencio, L. R. (1991). Strength Evaluation of Early Age Shotcrete. *Special Publication*, *128*, 273-288.

[10] Mohajerani, A., Rodrigues, D., Ricciuti, C., & Wilson, C. (2015). Early-age strength measurement of shotcrete. *Journal of Materials*, *2015*.

[11] Fenner, R. (1938). Untersuchungen zur Erkenntnis des Gebirgsdruckes, Glückauf, 74 (1938), 705-715.

[12] Brady, B. H. and Brown, E.T. (2013). Rock mechanics: for underground mining, Springer Science & Business Media, 312-322.

[13] Pöttler, Rudolf. "Time-dependent rock—Shotcrete interaction a numerical shortcut." *Computers and geotechnics* 9.3 (1990): 149-169.

[14] Weber, J.W. (1979) Empirische Formeln zur Beschreibung der Festigkeit-sentwicklung und der Entwicklung des E-Moulus von Beton. Betonwerk und Fertigteiltechnik, 45(12).