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Numerical Study on Interface Parameters of Sprayed Waterproofing Membrane by Direct Shear Test

*Chulho Lee[1] , Kicheol Lee[2], Dongwook Kim[3], Soo-Ho Chang[4], Soon-Wook Choi[5] and Byungkuan Park[6]

[1), 4), 5)] Geotechnical Engineering Research Institute, Korea Institute of Civil Engineering and Building Technology, 283 Goyang-daero, Ilsanseo-gu, Gyeonggi-do, 10223, Korea
[2), 3)] Dept. of Civil and Environment Engineering, Incheon National University, 119 Academy-ro, Yeonsu-gu, Incheon, 22012 Korea
[6)] Smart City & Construction Engineering, University of Science and Technology, 217, Gajeong-ro, Yuseong-gu, Daejeon, 34113, Korea
[1)] chlee@kict.re.kr

ABSTRACT

A waterproof membrane sprayed onto concrete enables faster construction with better waterproof performance compared with a conventional sheet membrane. However, waterproof membranes have not been widely used despite of their outstanding structural properties, which include higher cohesion at the interface and higher tensile strength compared with those of conventional materials. In this study, the material properties and contact surface characteristics of waterproof membrane were obtained through comparisons of laboratory experiments and numerical analysis. The material properties were determined by tensile test and were derived using plastic model. The contact surface characteristics were obtained through direct shear test, and appropriate values were extracted using various contact surface models.

1. INTRODUCTION

In underground structures, water flow and waterproofing are the most economical and effective ways to maintain the design life of the structure with safety and structural improvements. Groundwater introduced during underground excavation is an important consideration because it can degrade the performance and durability of the structure (Nakashima et al., 2015). In particular, excessive leaks can cause construction costs to increase and construction delays during construction. In addition, it can lead to an increase in the maintenance cost and the durability life of underground structures during operation (ITAtech, 2013). Therefore, a sheet waterproofing membrane made of

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[1)] Senior Researcher
[2)] Graduate Student
[3)] Associate Professor
[4)] Senior Research Fellow
[5)] Research Specialist
[6)] Graduate Student

a material such as PVC is generally used for the underground excavation section. However, since the concrete lining is generally applied after installing the waterproofing membrane, it is difficult to prevent leakage of water if the waterproofing membrane is damaged during the lining of the concrete. Accordingly, materials having high adhesion performance such as a spray-applied waterproofing membrane have recently been utilized. This can be combined with shotcrete lining to manifest its function as a composite structure and thus reduce the thickness of the lining (Holter, 2015).

A waterproof membrane sprayed onto concrete enables faster construction with better waterproof performance compared with a conventional sheet membrane. However, waterproof membranes have not been widely used despite of their outstanding structural properties, which include higher cohesion at the interface (Lee et al., 2017) and higher tensile strength compared with those of conventional materials.

Therefore, this study evaluates interface properties of a waterproof membrane based on the results from laboratory experiments (tensile test and direct shear test) according to thicknesses of waterproof membrane. From the series of laboratory tests, material properties of waterproof membrane and interfacial shear strength between membrane and shotcrete were suggested.

2. Material properties of waterproof membrane

The tensile test was carried out to determine the material properties of the waterproof membrane. Based on the strain-stress curves derived from the tensile test, the material properties of the waterproof membrane were traced using ABAQUS/CAE which is a numerical analysis program.

2.1 Tensile test

Since the thickness of the specimen used in the tensile test was 3 mm, the tensile test was conducted in Type IV according to ASTM-D638 (ASTM, 2010). ASTM specifies specimen sizes for Type IV when the specimen thickness is less than 4 mm.

The tensile test results are shown in Fig. 1. As shown in the figure, the strain of the initial elastic section of the waterproof membrane showed about 2 % and then showed the characteristic of the ductile material.

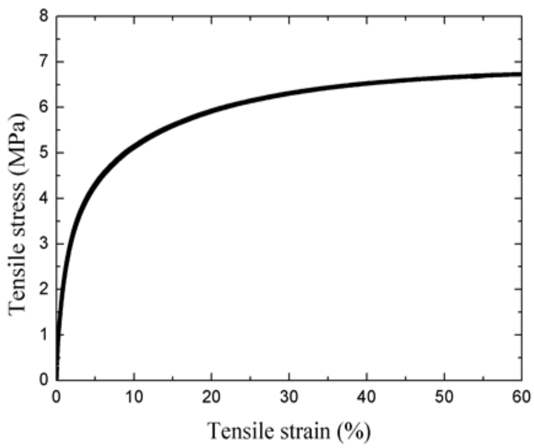
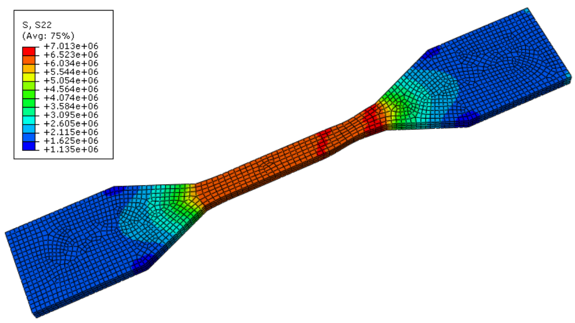


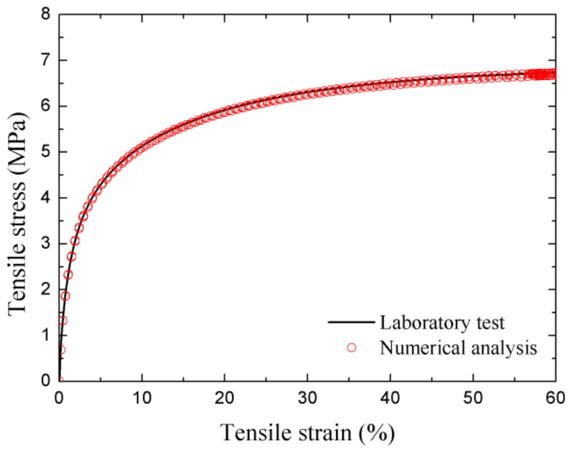
Fig. 1 Tensile stress-strain curve of waterproof membrane

2.2 Numerical analysis for back tracking of material properties

For the analysis, a plastic material model suitable for materials with high tensile ratios such as waterproof membrane. It is difficult to simulate the plastic behavior after the elastic section if only the basic Elastic model is applied. Therefore, the mixing behaviors of Elastic model and Plastic model were simulated. The elastic modulus, Poisson's ratio, and Plastic conditions of the waterproof membrane were changed to match the laboratory test results and the numerical analysis results.

The modeling used for the analysis is shown in Fig. 2 (a), and the comparison between the laboratory and the numerical results is shown in Fig. 2 (b). The elastic modulus of the waterproof membrane was found to be 382.92 MPa and Poisson's ratio is 0.3.





(a) (b)

Fig. 2 Numerical analysis for *back tracking of material properties;* (a) Modeling of tensile test and (b) Comparison between laboratory test and numerical analysis

3. Contact properties of waterproof membrane

3.1 Tangential behavior of interfaces

In the direct shear test, the contact characteristic of the shear surface is one of the important factors. The shear force may be different depending on the contact characteristics. When surfaces are in contact, they usually transmit shear and normal forces across the interface (SIMULIA, 2014). In the direct shear test, tangential behavior-penalty method was applied to the analysis method because there is generally friction in shotcrete and waterproof membrane. The method is based on the friction coefficient, assuming ideal behavior, and there is no slip during contact. This method is based on the Coulomb friction model as the default setting (Fig. 3). Where, τ_{cr} is the critical shear stress μ is friction coefficient and P is contact pressure.

These models show the following four characteristics (Kim, 2014). (1) Critical friction stress depends on contact pressure; (2) $\tau_{cr} = \mu P$; (3) The coefficient of friction can be a function of relative slip velocity, pressure, temperature, field parameters, etc; (4) The basic set of friction models uses an approximation of the ideal behavior. It also permits a small amount of resilient slip before irreversible slip occurs.

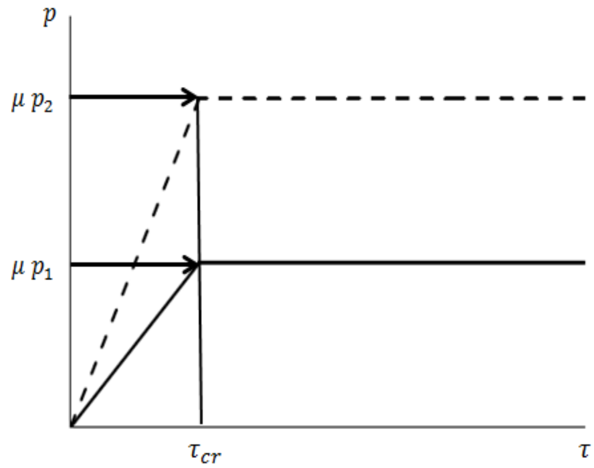


Fig. 3 Coulomb friction model (modified after Kim, 2014)

3.1 Cohesive and damage behavior of interfaces

The 'HARD contact' model, which is used as a general contact model, minimizes the penetration at the contact surface and does not allow the transition by the penetration at the contact surface. However, since the waterproof membrane used in this study is a material that depends on the cohesion force, it should not allow penetration in the analytical model, and should be removed only by cohesive force.

In addition, the damage model should be applied so that when the cohesion of waterproof membrane and shotcrete reaches a certain level, they disappear. In general, the damage model for contact defines the initiation and evolution of damage. Figure 4 is a conceptual diagram of the cohesion and damage model of the contact surface. When the maximum stress (t^{max}) at the contact surface in the cohesion model reaches the contact separation maximum load (δ^{max}), damage begins to occur. At this time, the stress on the contact surface is gradually reduced, and finally, the fracture occurs to completely separate the contact surface.

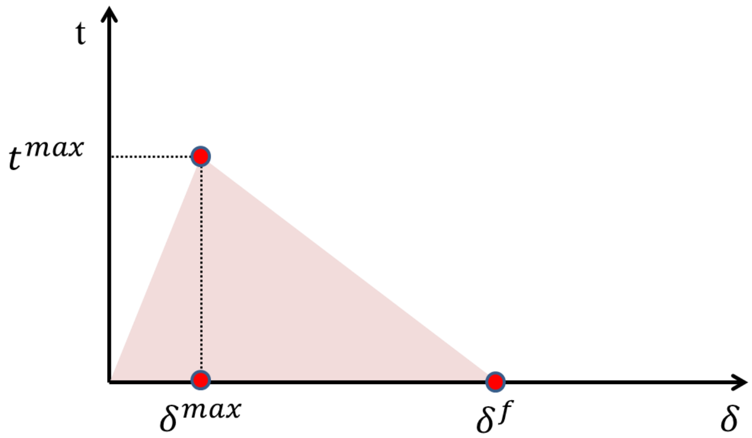


Fig. 4 Traction-separation relationship of cohesive and damage contact model (modified after SIMULIA, 2014)

3.3 Direct shear test

Direct shear test was conducted to investigate contact properties between shotcrete and waterproof membrane. The specimen of direct shear test is consisted of a waterproof membrane between the two shotcrete specimens. The size of each shotcrete specimen is 10 cm (Width) x 10 cm (Length) x 7.5 cm (Height). The thicknesses of waterproof membrane are 3, 5 and 7 mm. The test method is shown in Fig. 5. Also, the vertical stresses (σ_n) are 0.3, 0.6, 0.9, 1.2 and 1.5 MPa.

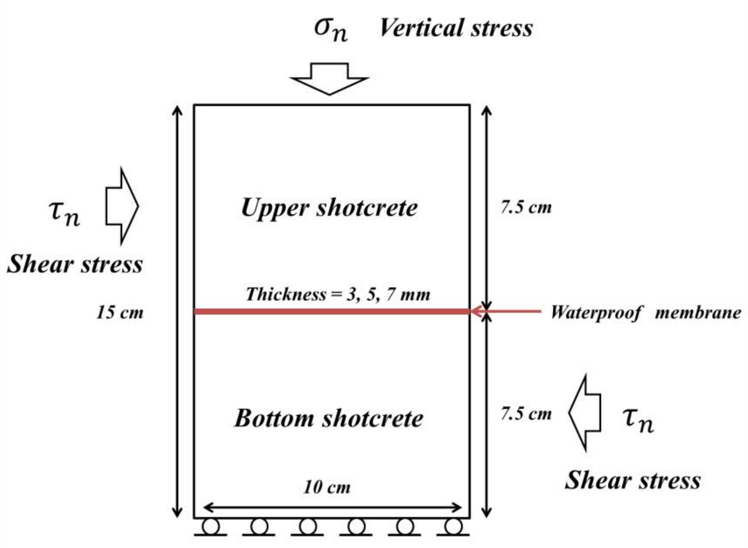


Fig. 5 The test method for direct shear test

The results of direct shear test are shown in Fig. 6 and Table 1. When the thickness of the waterproof membrane is 3 mm, the shear strength tended to increase as the normal stress increased. However, when the thicknesses of waterproof membrane are 3 mm and 5 mm, the shear strength is similar regardless of vertical stress.

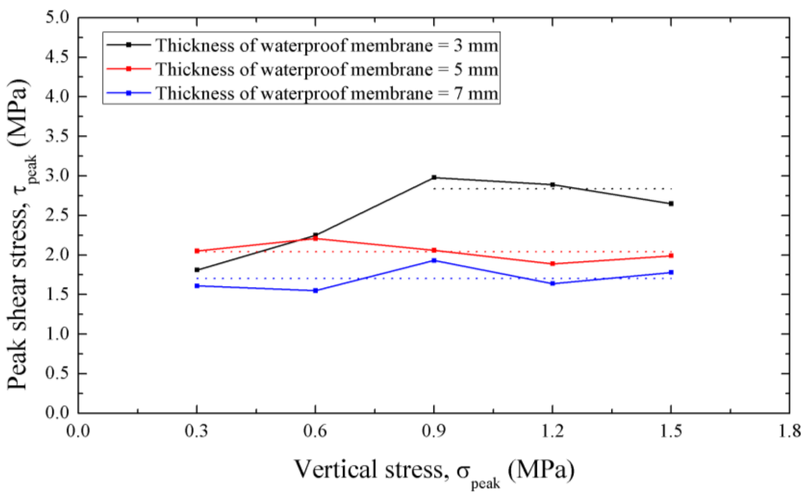


Fig. 6 Results of direct shear test; shear strengths at different vertical stress conditions of specimens

Table 1 Results of direct shear test according to vertical stresses

	Vertical stress, σ_n (MPa)	Thickness of waterproof membrane		
		3 mm	5 mm	7 mm
Peak shear strength, τ_{peak} (MPa)	0.3	1.81	2.05	1.61
	0.6	2.25	2.21	1.55
	0.9	2.98	2.06	1.93
	1.2	2.89	1.89	1.64
	1.5	2.65	1.99	1.78

3.4 Numerical analysis for back tracking of contact properties

The actual direct shear test was simulated numerically for the contact properties of shotcrete and waterproof membrane. Figure 5 was numerically modeled in two dimensions.

When the actual waterproof membrane was inserted into the upper and lower shotcrete, the progress and tendency of the analysis did not appear due to the compression and deformation of the material. In addition, since the shotcrete is set as the beam member in the actual design, it is difficult to reflect it into the design when the heterogeneous material is inserted between the beam members. Therefore, the waterproof membrane material was removed from the contact characteristics analysis. After attaching the upper and lower shotcrete, contact characteristics of the waterproof membrane were determined.

The shear stresses were independent of the vertical stress except when the thickness of the waterproof membrane was 3 mm. Therefore, the cohesive and damaged model, which is not influenced by the normal stress, is applied to the overall contact characteristics. The frictional coefficient is calculated by the tangential behavior when the thickness is 3 mm and the normal stress is 0.3 MPa and 0.6 MPa. The analysis results are shown in Table 2.

Table 2 Interaction properties with thicknesses of waterproof membrane

Tangential behavior model		
Thickness	Vertical stress, σ_n (MPa)	Friction coefficient
3 mm	0.3	4.53
	0.6	2.26

Cohesive and damaged model			
Thickness	Cohesive stiffness (GPa)	Maximum nominal stress at damage initiation (MPa)	Fracturing energy (kJ/m^2)
3 mm	0.75	2.05	9.2
5 mm	0.80	0.7	8.0
7 mm	0.85	0.1	6.0

4. CONCLUSIONS

In this study, numerical analysis was carried out based on experimental results in order to understand the contact characteristics of waterproof membrane with thickness. The conclusions of the numerical analysis are as follows.

1. In general, the waterproof membrane proposed in this study showed that the shear strength was constant regardless of the vertical stress. The shear strength decreased with increasing thickness. However, when the thickness is thin and the vertical stress is small, the shear strength tends to increase with increasing vertical stress.

2. Waterproof membranes generally exhibit cohesive and damaged behavior. However, when the thickness is thin and the vertical stress is small, the tangential behavior affected by the friction coefficient is exhibited.

3. Cohesive stiffness is increased, but maximum nominal stress at damage initiation and fracturing energy tend to decrease with thicker thickness in cohesive and damaged behavior.

ACKNOWLDEGEMENT

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