地山改良のためのウレタン系注入材の固結特性に関する研究

Study on Solidification Characteristics of Urethane Grout for Ground Improvement

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要　旨

山岳工法によるトンネルにおいて，軟弱な地山や坑口部の施工における切羽安定対策として各種補助工法が採用されている。特に，切羽・天端の安定対策として手軽に採用でき，しかも限定注入が可能であるウレタン系注入式フォアポーリングは補助工法として有効な工法の一つといえる。ウレタン系注入式フォアポーリングは実施工において採用実績が多いにもかかわらず，ウレタン系注入材が地山に注入されたのち発泡し固結するという注入材の特性のために，その固結特性については他の注入材であるセメントミルクや水ガラス系注入材に比べ研究されたものがわずかに見られる程度であった。さらに，ウレタン系注入材の材料単価が他の注入材に比較して非常に高価であることから，合理的な設計・施工が求められている。

そこで，本研究は，ウレタン系注入式フォアポーリングを合理的に設計・施工を行うための有用な情報を与える目的で，ウレタン系注入材の固結改良特性を明らかにするために室内実験および現場実験により固結特性を明らかにした。また，ウレタン系注入材として通常のウレタン注入材の有用な性質を確保した上で，より安価な材料であるシリカレジン注入材（ウレタン系注入材のひとつ）の開発過程と基本的性質についてもまとめた。

以下に本研究に関して要約したものを示す。

１）ウレタン系注入式フォアポーリングの工法の特徴と現状の適用

本研究の目的としているウレタン系注入式フォアポーリングの山岳トンネルの補助工法採用にあたっての特徴，施工方法およびその採用状況について調査した結果について述べ，標準設計を提案するとともに，本研究の意義を明確にしている。

２）ウレタン系注入材の開発と基本的性質

ウレタン系注入材として，通常のウレタン注入材の有用な基本性質を有した上で，材料価格を低減したシリカレジン注入材の開発ステップと注入材としての基本的性質について，従来のウレタン注入材と安全性，施工性，改良性，経済性の観点から比較しながら述べている。特に，他の注入材と比べ注入後に注入材自身が発泡するという特徴を有することから，これらの性質についても明らかにした。

３）ウレタン系注入材の固結特性に関する室内実験

まず，ウレタン系注入材の混合後の粘性が単体の液体の粘性と大きく異なることから，実験により確認した上で，３種の代表的な模擬地山として，礫，まさ，山土を用いてウレタン系注入材の固結特性を把握し，模擬地山を用いて特徴的な固結形状を分類した。また，注入方法として注入量の増加による成長過程，注入速度による固結体形状への影響，地山注入改良体の内部構造についても検討した。次に，改良の特徴である注入固結形状について，代表的な模擬地山での評価を更に一歩進め，３号～８号硅砂を用いて，模擬地山の透水係数の相違による固結特性の違いについても明らかにした。これにより，注入対象である地山の透水係数がわかれば，おおよその固結形状の想定が可能となった。また，ウレタン系注入材の特徴であるウレタン系注入材自身の発泡圧力について，地山に注入後どの程度の発泡圧力を有するかいままで解明されていなかったことから，その発泡圧力を確認すべく，硅砂模擬地山を用いて注入材の発泡圧力についても明らかにした。

４）ウレタン系注入材の固結特性に関する現場実験

室内実験で明らかになった現象について，実際の地山においても同様な固結特性が得られるかについて，強風化岩盤の切土斜面を対象に，ウレタン系注入材および従来から多用されているセメントミルク，ＬW注入材について実験を行い，固結体の生成過程を確認した。また，同時にまさ盛土を対象にした現場実験によりウレタン系注入材の固結特性を把握した。これらの結果から，室内実験で定義した固結形態の分類と地山条件別の固結特性を明らかにした。さらに７種類の地質12地点に対して現場実験を行い，改良固結特性について明らかにするとともに，室内実験で得られた透水係数の違いによる固結形態の変化についても，現場実験でも同様の形状を示すことを確認した。

＊ 技術第二部

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５）難浸透性地山におけるウレタン系注入材の固結特性

実地山で遭遇するケースの高い互層地山における改良固結特性について，実際の地山での試験が非常に困難であることから，礫，まさ，粘土を用いて模擬地山により互層地山を作成し，互層地山での改良固結体の固結特性について明らかにした。

キーワード：トンネル，地山注入，ウレタン，固結特性，材料開発，補助工法

Summary

In mountain tunneling construction, execution in soft grounds and at the tunnel portal part usually requires various auxiliary methods for stabilizing the face. Especially for stabilizing the tunnel face and crown, among auxiliary methods forepoling with urethane-line grouting, being easy to handle, and moreover, being able to perform restricted grouting, is considered one of the most effective construction methods.

Regardless that forepoling with urethane-line grouting has been employed in numerous actual construction works on actual grounds, however solidification characteristics of urethane-line grouts need to be investigated comprehensively since their special properties to expand like foam and solidify after being injected to the grounds are distinguished from other grouts such as cement milk line or water-glass line. Furthermore, since unit price of urethane-line grouts is too high compared to other grout materials, understanding their solidification characteristics is also necessary for rational design and construction.

In this study, for the purpose of effectively prediction in rational design and construction of forepoling with urethane-line grouting, solidification characteristics of urethane-line grouts have been clarified through laboratory and site experiments. Beside that, among urethane-line grouts, a material named silica resin grout, which secures all effective properties but relatively cheap in price, was under process of development. Its basic properties are also concluded. This paper reports related results of the study.

Chapter 1: Introduction

Existing state of applications and purposes of urethane-line grouts, the reality of employing forepoling with urethane-line grouting as construction method in mountain tunneling, as well as the solidification characteristics of urethane-line grouts are stated. Problems for studying are recommended.

Chapter 2: Urethane-line grouting specifications and actual applications

For the purpose of utilization of forepoling with urethane-line grouts as an auxiliary method in mountain tunneling, specifications, construction method and application conditions are reviewed and reported to emphasize the significance of this study.

Chapter 3: Urethane-line grout development and its basic properties

Development situation and basic properties of a material, named as silica resin, which can secure all the basic characteristics of common used urethane-line grouts, but relatively cheap in price, is reported. It is compared with the so far used urethane-line grouts by referring to safety, constructiveness, ground improving capability and economical… Especially, the property of self-foaming (self-expanding) after injection of the new developed grout, which makes it differed from other grouting materials, has been confirmed.

Chapter 4: Examination of urethane system grout solidification characteristics by laboratory experiments

Actually, it was confirmed from laboratory experiments that after mixing the urethane-line grout is a homogeneous liquidity viscous material, which enlarged in volume. Three representative types of model grounds made of gravels, decomposed granite soil (masado), and mountain soil, respectively, are subjected to injection of

urethane-line grouts to investigate their solidification characteristics. Based on that, typical solidified shapes are classified according to model ground's characteristics.

Beside that, effects from grouting method, such as increasing injected grout quantity to the process of formation of improved solidified bodies, or injection speed to the shape of the solidified bodies are also investigated by examining the inner structures of the grouting improved bodies.

Estimation of characteristics of the grouting improved ground in accordance with its solidified shapes is suggested step by step as following: use No.3 to No.8 sands for creating representative model grounds and subject them to grouting injection; then establish the dependency of solidified characteristics on variation of coefficient of permeability of model grounds. Based on that, when the coefficient of permeability of actual soil subjected for grouting improvement is known, prediction of expected solidified shapes becomes possible.

Next, about the special property as self-foaming (self expanding), the magnitude of the self-foaming pressure after injection of urethane-line grout onto the ground, which is so far not yet clearly understood, is thoroughly examined and clarified in this study.

Chapter 5: Examination of urethane-line grout solidification characteristics by site experiments

To clarify whether or not solidification characteristics of urethane-line grouts obtained at the site with actual grounds are similar to that understood from the laboratory experiments, a cut-slope in heavily weathered ground is selected to conduct site grouting treatment experiments with several types of grouts: urethane-line grout, common used cement-milk grout, and LW (Labiles Wasser Glass) grout. Processes of formation of solidified bodies from injection of different grouts are examined. Beside that, solidification characteristics of urethane-line grouts are also investigated from other experiments simultaneously conducted on decomposed granite soil (masado). From the results, classified solidified shapes of grouting improved bodies (already defined from laboratory experiments) and solidification characteristics of each actual ground condition have been clarified.

On the other hands, site experiments are also performed on 7 soil types at 12 locations in order to clarify the improvement solidification characteristics. Different solidified shapes of grouting improved bodies in accordance with differences in coefficient of permeability of the grounds are also confirmed similar to that obtained from laboratory experiments.

Chapter 6: Urethane system grout solidification characteristics on difficult permeable ground

Since in case of actual ground deposit encountering multi-layer soils, site grouting experiments are exceptionally difficult to perform, therefore, a multi-layer model ground has been created from gravels, decomposed granite soil (masado) and clay to investigate the improvement solidification characteristics of grouting improved bodies in multi-layer soils.

Chapter 7: Conclusions

In conclusions, the research results are summarized in accordance to the topics in each chapter, and research subjects related to the field of utilization of urethane-line grouts are reported.