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Interface behavior of tensioned bars embedded in cement-soil mixtures

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HIGHLIGHTS

- A newly designed testing setup and protocol for interface characterization of rebar embedded in cement-soil mixtures.
- A prediction model for interface bond strength by using water-cement ratio and curing time.
- A simplified rebar-mixture interface bond-slip model.
- Recommendations benefiting the design and construction practice.

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ABSTRACT

The overall performance of reinforced cement-stabilized soils depends significantly on the interface bond mechanisms that develop between the reinforcement and the surrounding cement-soil mixture. A laboratory experimental investigation based on uniform design theory was carried out to characterize the interface behavior of deformed bars embedded in cement-admixed soils. The study focused on the influence of cement content, water content and curing duration on the interface response. The interface bond strength of reinforced cement-soil mixture, as measured in pullout tests, was found to be proportional to the strength of cement-soil matrix, as obtained from unconfined compression tests. A simplified trilinear bond-slip model was developed as part of this study, which when properly calibrated was found to be capable of characterizing the bar-mixture interface shear response. Correlations were obtained to relate the interface bond strength with the three influence factors investigated in this study. The trends obtained on the influence of each factor on the interface bond resistance provided insights that were suitable to guide current design and construction practice of reinforced cement-soil mixture. The results and testing protocols presented in this study facilitated the understanding for interface shear mechanism between deformed bar and cement-soil mixture, and are expected to provide adequate means to satisfy the current lack of bar-mixture interface bond parameters in design specification for reinforced soil mixing structures.

1. Introduction

Cement has been recognized as one of the most important binders/admixtures in geotechnical engineering for ground improvement and stabilization, especially in soft or contaminated clays and sludge [1,2]. Using techniques of soil mixing and jet grouting, cement or slurry can be introduced into the pores of naturally weak soils resulting in pozzolanic reactions forming soil-cement mixtures of improved characteristics [3]. Many research studies were conducted to investigate the improved mechanical and hydraulic properties of cement-stabilized soils, such as strength increase, permeability decrease, and compressibility reduction [4–18].

Stabilized soil systems in some special applications, such as cement mixing columns, are used in excavation support and ground water cut-off solutions, and are unavoidably required to withstand lateral earth pressure [19–22]. This motivation inspired the development of reinforced cement-stabilized soils by introducing reinforcements into cement-soil mixtures. Two different methods are commonly used to introduce reinforcements into cemented soils according to their type. One method uses reinforcements, typically fibers, as additives distributed uniformly over the entire volume of the cemented soil mass to form a composite material with customized cement and fiber contents. This composite material is characterized by a bond interface between fibers and cemented

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soils, and is reported to exhibit highly improved mechanical properties [23–25]. The second method employs reinforcements as structural elements that bind with the cemented soil mass to resist external loads by mobilizing interface bonds on a specific and continuous interface [26], similar to reinforced concrete. The scope of this study focuses on the bond behavior of this continuous interface, which was specifically formed between the reinforcement rebars and cemented soils, referred to as reinforced cement-soil mixtures. A common application of reinforced cement-soil mixture is Soil Mixed Wall, which was firstly applied in Japan and extensively accepted as a geotechnical solution in soil retention applications [2,27]. Another typical application of reinforced cement-soil mixtures is use with a cement-soil mixing anchor. These anchors can be installed simultaneous with drilling, homing and grouting, unlike the installation of conventional anchors, which requires sequential drilling-homing-grouting procedures. This offsets the difficulty of drilling holes in soft soils. Using this type of anchor can effectively extend the applicability of anchorage techniques to regions characterized by the presence of soft soils [26,28–31].

The pullout resistance of reinforcement embedded in cement-soil mixture depends on the interface shear behavior of the reinforcement and the cement-soil matrix through mechanisms similar to those of reinforced concrete [32]. Structural responses of anchor plates in cement-stabilized backfill and reinforced cement-soil beam were investigated [33,34], whereas studies with exclusive concerns on interface shear response of reinforcement in cement-soil matrix are not yet reported. Consequently, current design specification of reinforced cement-soil structures [26] is deficient in this respect that bond strength of rebar-matrix interface is not considered in the determination of ultimate pullout resistance of reinforcement. It is the case particularly for cement-soil mixing anchor, where the critical role of reinforcement-matrix interface characteristic is emphasized, but relevant quantitative recommendations are not available in design guidelines.

Cement-soil mixture is constituted by four phases, refer to as cementitious solid, soil solid, water and air, typically in condition of being cured for 28 days. As a composite material, it is distinguished from natural soil by the presence of cementitious solid in composition and higher porosity, and from concrete by the introducing cohesive soils instead of cohesionless aggregates [35]. Interface bond strength of reinforcement embedded in soil-cement matrix is gained through cement hardening mechanisms similar to that in concrete matrix. Accordingly, element pullout test used in the characterization of bond performance for reinforced concrete [32,36], is adopted in this study to investigate interface behavior of deformed bar in cement-soil mixture.

It is known that the strength of a cement-soil mixture depends mainly on cement content, water content, and curing period with respect to a certain amount of to-be-treated soft soils [1,11,16]. These three factors were justified to be extensively accounted for in experimental characterization of interface behavior of a certain reinforcement, specifically using deformed bar in this study, embedded in cement-soil matrix. Varying levels are needed for each factor investigated in pullout testing program aiming to obtain their influence patterns on interface bond strength, which thus defines a multi-factor by multi-level experimental program. For a problem with m-factor by n-level, testing program based on full design will lead to a total number of specimens by m^n. While the number of levels is increased in investigation, challenges will be raised substantially in laboratory labor of specimen preparation and consistency control of different specimens. Optimization tools were introduced to implement elaborated design on combination of levels for all factors imposed on each specimen [37,38]. Uniform design theory stands out in these competitive tools by the capability of reducing required specimen quantity substantially from m^n to m with uniformity implied in test results acceptably retained. It should be noted that engineer-accessible uniform design tables are available to identify the level combination of all factors imposed on each specimen. Direct use of these tables eliminates the difficulties in understanding complicated mathematical fundamentals underlying uniform design theory [37]. Reported cases exemplified the applicability of uniform design theory to geotechnical experimental investigations [39–42], and justified the consecutive application to designing this three-factor and multi-level testing program as described earlier.

This study presents an experimental characterization of the interface behavior of a deformed bar embedded in cement-stabilized soils. A number of pullout tests and compression tests were conducted on reinforced cement-soil mixture specimens and cubic cement-soil matrix specimens, respectively. The influence of water content, cement content and curing period on interface shear response was examined through a testing program based on uniform design theory. Interpretations on test results were incorporated into a simplified bond-slip model to characterize interface behavior between reinforcement and cement-soil mixtures. Correlations were developed to associate interface bond strength with testing parameters, of which on basis discussions were conducted to provide insights to current practice of reinforced cement-soil mixture.

2. Testing program

Cement-soil mixture is generally produced in situ by wet/dry soil mixing or jet grouting. Fig. 1a illustrates the phase composition for typical cement-soil mixtures. It is noteworthy that the water content of cement-soil mixture depends on three factors: (a) the method of cement introduction (dry powder or slurry); (b) the moisture condition of the natural soil; (c) the undergoing degree of the hardening process [2]. As shown in Fig. 1b, the influence factors involved in this testing program were defined based on in-situ dry mixing method as follows: (a) water content (C_w), which represents the mass ratio of the added water and the dry soil skeleton; (b) cement content (C_c), also referred to as moist cement content in literature [3], which represents the mass ratio of the cement and the summation of both dry soil skeleton and added water.

Soft clays that are practically suitable for cement stabilization are usually characterized with moisture contents larger than 35% or close to liquid limit. The selection of cement content is optimized such that it provides the best stabilization efficiency, which is soil-specific, with the optimum amount of water based on its availability. In such cases, the optimal cement content is typically less than 30% [3,4,11]. Accordingly, the cement content and water content adopted in this experimental study ranged from 5 to 30% and 45 to 90%, respectively. Cement-stabilized soils were observed to complete hydration and hardening to its full strength in a 90-day curing period. However, strengths with shorter curing periods (e.g. 15 days to 30 days) were commonly applied in design as alternatives due to tight construction schedules in practice [3,43]. Consequently, curing duration (denoted by T_c) adopted in this experimental study ranged from 7 days to 28 days to allow for the evaluation of the interface bond strength increase with time.

The experimental program involved tests conducted at six cement contents, four water contents, and three curing periods, as shown in Table 1. A testing scheme was developed based on the application of uniform design table $U^{*}12(12^{10})$ [37] to the aforementioned three testing factors, as shown in Table 2. Note that, in $U^{*}12(12^{10})$, the integer of 12 denotes the required number of levels for each testing factor using this uniform design table, and the integer 10 denotes the maximum number of testing factor applicable to this design table. The number of levels for the three testing factors in this study (Table 1) were extended accordingly