論文の内容の要旨
Thesis Summary

Experimental Study on Loading Rate Dependent Mechanical Behavior of Artificially Bounded Geomaterials

(人工的に固結させた地盤材料の載荷速度依存性を有する力学挙動に関する実験的研究)

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In the present era of infrastructure development, the need of "Sustainable Construction" is deemed indispensable among stakeholders and policy makers associated with construction industry. The philosophy of "Sustainable construction" is not only limited to the construction phase but also includes the efficient deconstruction of infrastructure and recycling/reuse of resources to minimize the waste materials produced during demolishing phase. In the past decades, emerging sustainability challenges have been posed by the gypsum plasterboard waste generated during the manufacturing, construction and demolishing phases of gypsum plasterboards, also known as drywall. For instance, Japan annually generates around 1.6 million tons of gypsum plasterboard waste, and the disposal of this waste often raise austere financial and environmental issues. Besides other financial and environmental issues, this waste is also prone to release toxic Hydrogen Sulfide (H2S) gas under moist anaerobic conditions.

Inspired from the above stated principles of "Sustainable construction", a process of recycling of gypsum plasterboard waste is adopted globally for the production of recycled gypsum, chemically known as "Bassanite" or hemi hydrate calcium sulfite ($CaSO_4.1/2H_2O$). Furthermore, the application of this recycled gypsum as a potential cementing/stabilizing agent in ground improvement projects and foundation works have recently gained attention of researchers. However, the long-term performance of gypsum mixed geomaterials is still dubious as the time-dependent strength and deformation behaviour of gypsum treated geomaterials has not yet been examined thoroughly.

It is also an established fact that the strength and deformation characteristics of bounded geomaterials are susceptible to change with time, known as "Time Effects", and are broadly

classified into ageing and loading rate (viscous) effects. Moreover, the long term performance of these geomaterials are governed by these “Time Effects”, In the present study, loading rate dependent behavior of artificially produced bounded geomaterials, viz. gypsum and cement treated geomaterials; are meticulously examined at a wider range of strain rates under unconfined and confined loading conditions. The role of loading rate dependency (viscosity) of these geomaterials in rational comprehension of the behaviour under creep and cyclic loading demands detailed investigation. Additionally, a thorough study of the effects of loading rate on the strain localization is considered essential to plausibly apprehend the deformation characteristics of these bounded geomaterials.

A number of laboratory produced specimens of Gypsum Mixed Sand (GMS) and Cement Treated Sand (CTS) were prepared by mixing Silica Sand No. 6, water, bentonite, and gypsum/cement. In order to assess the reliability of the obtained test results, a criterion based on the absolute value of average difference between the local strains measured at the opposite ends of specimen was proposed. This criterion proved to be vital to scrutinize the reliable results for further analysis.

The effects of ageing were examined by conducting a series of unconfined monotonic tests on GMS and CTS specimens cured at different periods of curing, ranging from 2 days to 9 months. A reduction of about 20% in Unconfined Compressive Strength (UCS) was witnessed for GMS specimen within first month of curing, and no effects of ageing were observed up to 9 months of curing. Under similar testing conditions, GMS specimens prepared by using different batches of gypsum showed significant differences in peak strength. This variability in strength is potentially associated with the presences of different impurities and additives, such as soluble calcium sulphate anhydrite, calcium sulphate dihydrate and potassium sulphate etc. On the other hand, a continuous increase in UCS for CTS specimens was observed during first month, and the UCS values were roughly constant afterwards, up to 6 months of curing.

The loading rate dependent behavior of GMS and CTS were examined at wide range of strain rates, ranging 2.0E-05 to 5.4E+00 %/min. (5 folds). A very unique and significant loading rate dependency of GMS was witnessed, as peak strength reduction of about 88% was reported with a decrease in strain rate by 120 times, viz. 2.4E-2 to 2.0E-4 %min. Moreover, pre-peak stiffness, failure strain and post-peak behavior of GMS was also found to be significantly governed by the loading rate. The effects of loading rate on the mechanical behaviour of GMS were divided into three distinct zones of strain rates, viz. Zones 1, 2 and 3. Substantial reduction in peak strength and pre-peak stiffness of GMS specimen with the decrease in strain rate was observed for specimens tested at strain rates lesser than 2.0E-3 %/min, viz. Zone-3. Moreover, the effects of different gypsum batches, gypsum content (G/S = 80% to 40%, where G and S stand for the weights of gypsum and sand, respectively) and curing conditions are negligible on the loading rate dependency of GMS.

On the other hand, relatively insignificant effects of loading rate on the mechanical behavior of CTS were observed. Such a prominent loading rate dependency of GMS is believed to be linked with the micromechanical peculiarities of GMS. Among these peculiarities is the inherent viscosity of the dihydrate crystals possibly due to the weak intermolecular forces. Additionally, the porous nature of interlocked needle-shape mass is also believed to induced relatively lesser frictional forces for crack propagation under slower loading rate

A series of creep and cyclic loading tests were also performed on GMS under unconfined conditions. The long-term performance of GMS under unconfined creep loading was proved to be very unpromising, and a creep load of even 32% of peak strength was able to trigger creep induced failure within 9 days. For both cyclic and creep tests on GMS, almost linear trend of axial strain accumulation with elapsed time was witnessed on full-logarithmic plot, followed by a rapid increase in axial strain values after the onset of failure. Moreover, the strain accumulation during creep was also observed to be significantly larger.

A unique relationship between the normalized failure stress and instantaneous failure strain rate of GMS specimens tested under unconfined creep and cyclic loading, and the behavior of GMS under unconfined creep and cyclic loading conditions are similar to each other and distinctively different than unconfined monotonic tests. Therefore, it is concluded that GMS is very weak against creep/cyclic loading, and long-term in-situ performance of GMS under such loading conditions is expected to be inauspicious compared with other bounded geomaterials. Contrarily, CTS specimens were found to be significantly resistant against unconfined creep loading, as they were able to sustained high creep loads of about 75% of peak strength for more than 45 days.

In order to study the combined effects of confining stress and loading rate dependency of GMS, a series of consolidated drained triaxial tests were performed up to 800 kPa. The loading rate dependency of GMS was found to be unaffected by the effects of confining stress, and only the post-peak responses of specimens were affected by the confining stress. In addition, the deformation behavior of GMS at different isotropic drained consolidation stress levels was also studied, and the results indicate a continuous accumulation of axial strain under such loading conditions.

The strain localization characteristics of GMS were also studied using Particle Image Velocimetry (PIV) method, and it was found that the failure pattern was also dictated by the loading rate. In case of GMS specimens tested at higher loading (Zone-1), formation of shear band specimens was found to be of progressive nature, and was formed immediately after the pre-peak strain softening. The negligible amount of vertical strain accumulation in major portion of specimen indicated that limited damage of the microstructure of GMS occurred at higher strain rates. However, in spite of the fact that no visible shear bands were observed for specimen tested at strain rates lesser than 2.0E-4 %/min (Zone-3), the results of maximum shear strain distribution showed the possible existence of multiple zones of strain localization which contributed to strength reduction at lower loading rates.