An Experimental Study on the Bearing Characteristics of Auger-Cast Pile Installed Using Expansive Mortar

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요 지

천공굴착을 선행하게 되는 배토형 auger-cast 말뚝의 경우, 굴착 및 지반교란에 의한 횡방향응력의 감소로 인하여 주면마찰력이 타입식 말뚝에 비해 작게 발휘되는 것이 일반적이다. 이러한 auger-cast 말뚝의 주면마찰력을 향상시킬 수 있는 방법으로 팽창제의 사용과 가압주입의 적용효과를 고찰하고자 다짐 조성된 화강풍화토 지반에서의 팽창성 몰탈을 사용한 auger-cast 모형말뚝의 실내실험을 실시하였다. 모형말뚝은 팽창제의 양과 주입방법, 그리고 토조가압의 조건들을 변화시키면서 모형토조안에 제작되었다. 실험결과 팽창제의 사용이 증가함에 따라 말뚝의 주면마찰력이 점점 증가하는 경향으로 나타났으며, 이러한 증가의 폭은 가압주입이 적용되었을 때 더 뚜렷하게 발생하였다. 일반 몰탈을 가압 없이 주입하여 시공한 말뚝의 주면마찰력과 비교하여, 가압주입 없이 팽창제만 사용된 경우, 그리고 팽창제와 가압주입이 병행되어 사용되어진 경우 각각 24%, 그리고 56%까지 주면마찰력이 증가되는 것으로 나타났다.

Abstract

The frictional capacity of auger-cast piles is often very small because of the disturbance of the soil surrounding the pile during the excavation process. Usage of expansive agents and a pressurized injection technique for auger-cast piles should improve the frictional resistance between pile and soil. This paper presents the test results of auger-cast model piles installed with expansive mortar in laboratory compacted weathered soil. The model piles were installed in a calibration chamber with a variation in the amount of expansive agent, the injection process and the chamber pressure. It was observed that the pile shaft resistance increases with the increased amount of expansive agent, and also increases when mortar is pressure injected. The shaft resistance increased up to 24% for the pile installed only with expansive mortar and increased up to 56% for the pile installed with the pressurized injection of expansive mortar, compared with that of piles with plain mortar.

Keywords : Expansive mortar, Model pile, Shaft resistance, Auger-cast pile, Calibration chamber

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1. Introduction

For the construction of in-situ cast piles, the relief of in-situ ground stress caused by auger penetration with soil displacement may often result in the decrease of shaft resistance. It was reported that such reduction of shaft resistance increases in proportion to the degree of ground disturbance. It was also reported that the bearing capacity of a bored pile in sand was 30 to 40% less than that of a driven pile of the same size(Aboutaha et al., 1993). Of several methods suggested to improve shaft resistance, the use of expansive mortar employs the self-expanding property of expansive cement in construction of piles. The radial expansion of mortar causes an increase of counter pressure between a pile and surrounding soil which increases pile shaft resistance.

Hassan et al.(1993) presented that the application of expansive concrete with high alumina cement in field bored piles in a clay-shale produced a 17 to 31% increase in shaft resistance compared with that produced by a pile with plain cement. Bijsterveld(1993) proposed the use of expansive mortar for bored piles and tension piles through the expanding tests on the expansive mortar and a numerical analysis on piles installed using expansive mortar.

In this paper, laboratory tests on model piles were performed through the use of a calibration chamber in order to study the applicability of the piling method using expansive mortar. Twelve load tests on model piles were carried out to investigate the followings:

(1) The influence of the amount of expansive agent on the shaft resistance of piles
(2) The influence of pressurized injection on shaft resistance of piles
(3) The load-transfer characteristics of shaft resistance of piles installed using expansive mortar
(4) The influence of the chamber pressure on the shaft resistance of piles

2. Expansive Agent

2.1 CSA-Type Expansive Agent

The expansive agents used in this research are of the CSA-type. CSA stands for Calcium Sulfo Aluminate. The chemical expression of the expanding reaction is as follows:

$$4CaO \cdot 3Al_2O_3 \cdot SO_3 + 6[CaO \cdot H_2O] + 8[CaSO_4 \cdot 2H_2O] + 74H_2O \longrightarrow 3[3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O] \quad (1)$$

The resultant of the above reaction produces calcium sulfo aluminate hydrate($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) which is called ettringite. Ettringite, as shown in Photo 1, is a relatively small crystal of several micrometers and is formed within micro-pores of the gel in a needle shape during the hardening period of the cement paste. This not only prevents shrinkage from drying during hardening but can induce expansion of the cement.

Photo 1. Ettringite (SEM for test pile P6)

2.2 Preliminary Tests of Expansive Mortar

Since both the expansion ratio and strength of mortar are sensitive to the ratio of expansive agent to cement, the selection of the mixing ratio is very important to design in-situ piles properly. The amount of expansion generally increases as the amount of expansive agent used increases. But, the excessive use of expansive agent may drastically reduce the strength of mortar, and the expansion pressure developed may reach levels that can result in the destruction of the mortar.

To determine the appropriate mixing ratio, preliminary tests were performed and basic properties of expansive mortar were obtained(Han, 1998). From the results of preliminary tests, mixing ratios shown in Table 1 were selected for the model pile tests.

Table 1. Properties of expansive mortar used

Expansive Agent Type/Mixing Ratio	Slump (cm)	Slump Flow (cm)	7-Day Compressive Strength (kg/cm^2)	Axial Strain(× 10^{-4})					
				Curing in Water				Curing in Air after 7-days	
				7Day	16Day	28Day	91Day	7Day	16Day
J Company 7%	26.5	64.3	396	6.57	7.04	7.7	6.8	7.75	-1.41
D Company 11%	28.5	78.5	387	22.30	29.11	31.7	33.7	23.00	13.38
D Company 13%	28.6	73	343	49.65	59.51	62.1	65.9	48.94	38.73

Two expansive agents produced by J Company and D Company were used in this research. The expansion of the expansive agent produced by J Company only compensates for shrinkage, while the expansive agent produced by D Company provides for expansion in excess of this amount. From the preliminary test results, it can be concluded that the expansion rate of expansive mortar produced by D Company is superior to that of J Company.

3. Testing Apparatus

The calibration chamber used in this study is shown in Fig. 1. The main components of the chamber consist of a steel cylinder and two steel plates. The height of the chamber is 100cm and the internal diameter of the steel cylinder is 76.4cm. In the top plate, a hole was drilled for the installation and loading to the model pile. A tubular side membrane was attached to the inner surface of the steel cylinder and a flat membrane was located at the bottom plate. They serve as the lateral and the vertical pressure membrane, respectively.

The scheme of tensile loading system used is shown in Fig. 2. Dial gauges were symmetrically placed at opposite sides of the loading system.

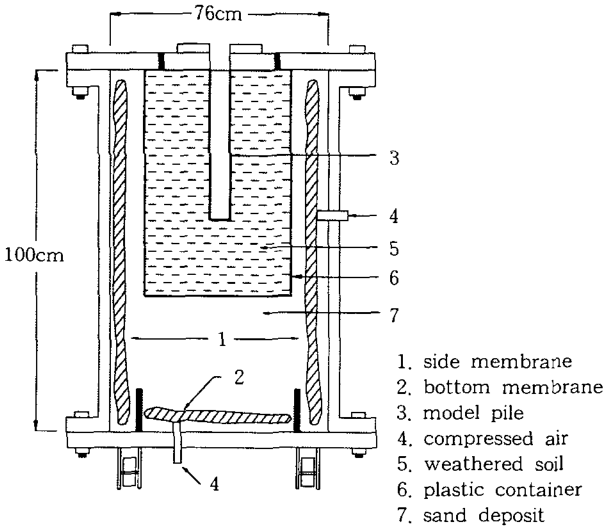

Fig 1. Calibration chamber

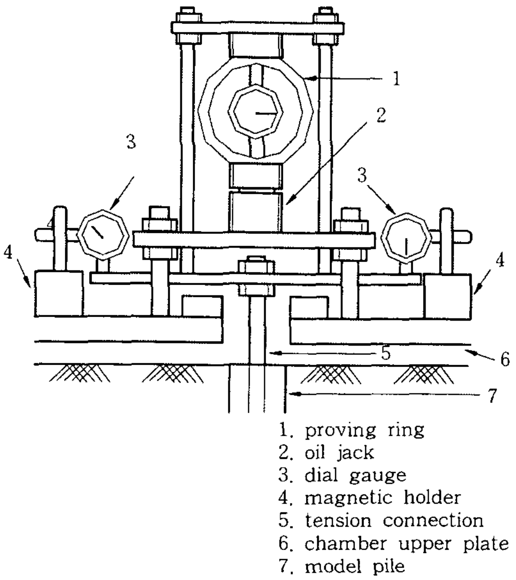

Fig 2. Tensile loading system

A special screw rod(Fig. 3) was fabricated and used for the tests to simulate the excavating operation for the construction of auger-cast piles.

The equipment for pressurized injection(Fig. 4) was made of acrylic material to inject mortar into a drilled hole. A sealing plate attached with o-rings is placed between the model ground and the upper chamber plate. This positioning prevents the leakage of both mortar and pressure, and the compressed air pressure is directly applied.

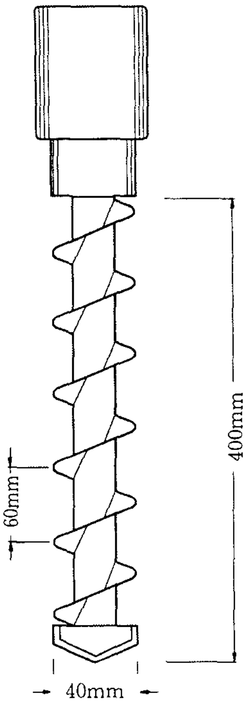

Fig 3. Screw rod

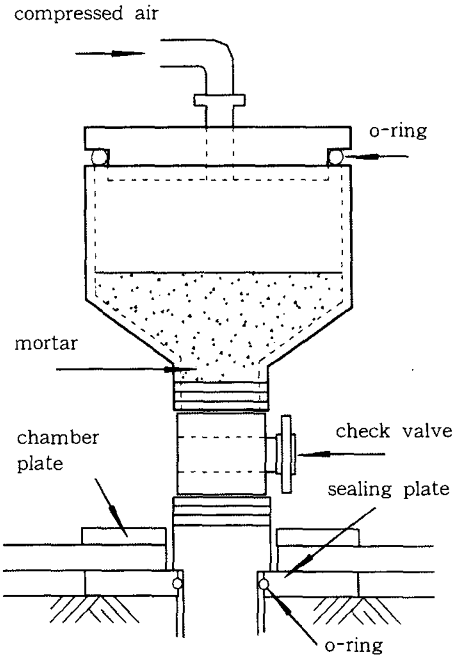

Fig 4. Pressurized injection equipment

4. Test Procedure

4.1 Sample Preparation

Because many construction sites in Korea are composed of residual soils of completely weathered granite soil, weathered granite soil was compacted to form the ground in the chamber. Since direct compaction of the granite soil within the chamber is not possible due to the possible damage to the membranes, the granite soil was compacted inside a separate plastic container which was later placed inside the chamber. Weathered granite soil was compacted in five layers by using a metal hammer of 7.5kg sliding in a tube which controls the drop height to 60cm. The water content of the weathered granite soil was controlled at 14% which is approximately the optimum moisture content obtained from the laboratory compaction test.

To form the sand deposit in the calibration chamber, the raining method was used. In this experiment, raining equipment with a clearance of 47cm between the sand bucket and the screen was used. The free-fall height from the screen(2mm size) was fixed at 56cm. Each sand layer was deposited to a thickness of 15cm. According to Lee and Lee(1993), a relative density of approximately 90% was achieved under the same procedure.

Once the sand deposit within the chamber is formed and the weathered granite soil is compacted in a plastic container, the plastic container is placed on the sand deposit, and the remaining space between the container and the side wall of the calibration chamber is filled with sand by the same raining procedure. After preparation of the specimen, the cover of the calibration chamber is assembled, and vertical and lateral pressures are applied for 24 hours. The boundary pressures applied to the chamber, i.e. $\sigma_v = 1.0\text{kg/cm}^2$, $\sigma_h = 0.4\text{kg/cm}^2$, represent the stress conditions at a depth of 11.4m in the field, on the assumption that the pressure applied to the model ground is determined by the stress conditions at mid-depth of a pile installed in the field.

The grain size distribution and properties of sand and weathered granite soil used are shown in Fig. 5 and Table 2, respectively.

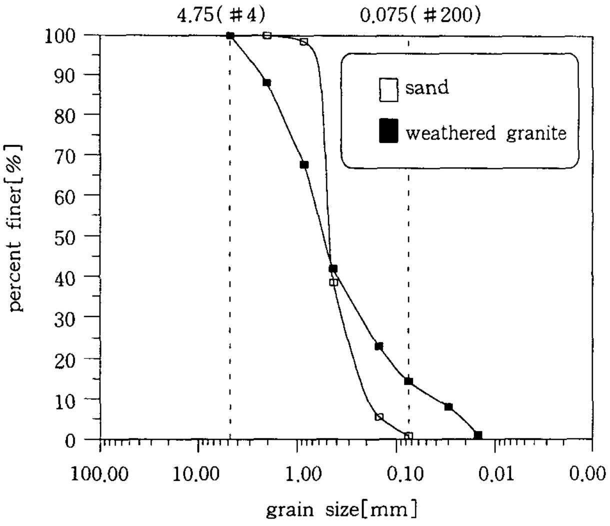

Fig 5. Grain size distribution of sand and weathered granite soil

Table 2. Properties of sample

Properties	Sand	Weathered Granite Soil
G_s	2.59	2.70
C_c	0.815	15.6
C_u	0.93	1.40
OMC(%)	–	14.3
γ_{dmax} (g/cm^3)	–	1.91
USCS	SP	SC

The water content, the unit weight and $\overline{CU}$ test results of weathered granite soil for the tests performed in this research are shown in Table 3.

Table 3. Water content, unit weight and $\overline{CU}$ test result of weathered granite soil for calibration chamber tests

Test Type	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	Ave.
Water Content (%)	13.9	13.8	14.1	14.1	14.0	14.2	14.0	14.1	13.9	13.8	14.0	14.1	14.0
Wet Unit Weight (g/cm^3)	1.74	1.76	1.77	1.74	1.75	1.77	1.77	1.77	1.75	1.77	1.76	1.78	1.76
Triaxial Test Result($\overline{CU}$-test)	c' (kg/cm^2)			0.1			ϕ' (degree)			32.7			

4.2 Installation of Model Pile

The model piles with expansive mortar were installed in compacted weathered granite by excavation of the ground and injection of mortar as shown in Fig 6. The excavation of ground was performed by using electric drilling equipment with the screw rod. Two injection methods were performed to study the effects on the shaft resistance of a model pile. Namely, injection with pressure and injection without pressure. For the injection without pressure, a pile was installed through careful pouring of mortar into a predrilled hole. For the injection with pressure, installation was achieved through the injection of mortar by the pressurized injection system shown in Fig. 4. Detailed conditions of test piles are described in Table 4.

Table 4. Types of model pile tests

Type of Expansive Agent	Plain			J Company		D Company						
Mixing Ratio**	none			7 %		11 %		13 %				15%
Pressurized Injection	×	○	×	×	○	×	○	×	○	×	○	○
Chamber Pressure	○	○	×	○	○	○	○	○	○	×	×	○
Pile Symbol	P1	P2	P10*	P3	P4	P5	P6	P7	P8	P11*	P12*	P9

*P10, P11, P12 were additionally tested after other pile tests

** the mixing ratio: ((weight of expansive agent)/(weight of expansive agent+cement))×100(%)

The effect of the pressurized injection may differ with the variation of injection pressure and injection speed, even under identical ground conditions. A pressurized injection procedure that maintained a constant pressure with each step (predetermined time and depth) was used in this research. To check if the effect of pressurized injection would be uniform in all tests, GF(ratio of injected volume to actual drilled volume, Grout Factor) was calculated for each test. From the test results by Neely(1991), it was reported that under the same ground conditions, the pile bearing

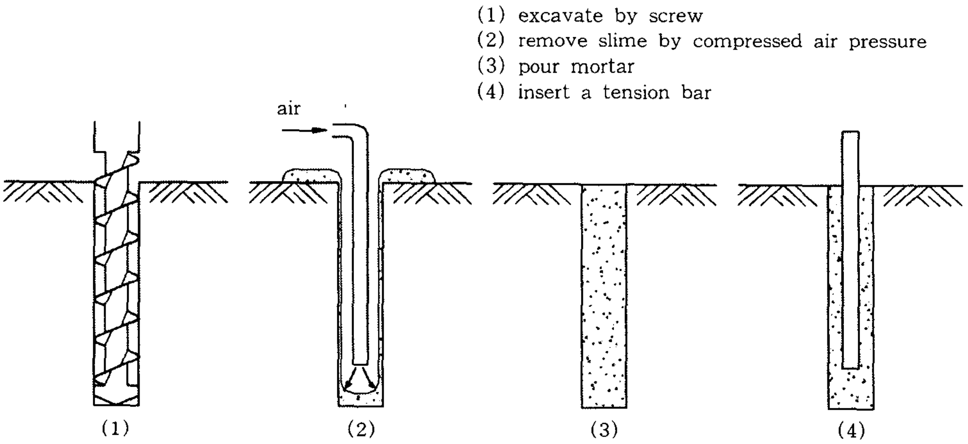

Fig 6. Installation of model pile

capacity increased in proportion to the increase in GF. On completion of the injection of the mortar, a tension bar of 50cm in length was inserted into the center of the pile. The pile was then cured for 7 days, and then the load tests were performed.

4.3 Loading Test Procedure

Tensile load tests were performed to investigate the characteristics of shaft friction of piles installed using expansive mortar. The load test used in this research was a 'quick maintained load test'. In this load test, the interval of maintained load at each loading stage was 5 minutes. The upward displacement was evaluated at 0, 2.5, 4 and 5 minutes. The load increments were approximately 90kg and the increase of load continued until ultimate load was reached. In most cases, the ultimate uplift capacity was reached at an uplift movement of 2.0~4.9mm or 5~12% of the pile diameter.

5. Test Results

5.1 Load Test Results

With boundary conditions of $\sigma_v = 1.0\text{kg/cm}^2$ and $\sigma_h = 0.4\text{kg/cm}^2$, tensile load tests on 9 model piles were performed and the load-displacement curves are shown in Fig. 7. The test results are summarized in Table 5.

In addition to the tests on the 9 piles mentioned above, load tests on 3 other piles were performed without chamber pressure to see the effect of chamber pressure on shaft resistance. The load-displacement curves are shown in Fig. 7 and the summary of the test results is described in Table 6.

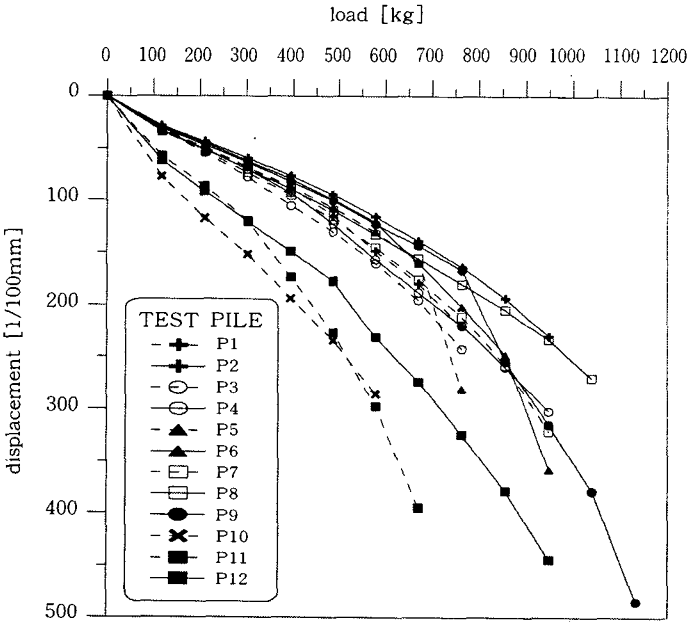

Fig 7. Load-displacement curve

Table 5. Load test results(with chamber pressure)

Pile Type	Pile Symbol	Ultimate Load (kg)	Pile Length (cm)	GF	Unit Shaft Resistance (kg/cm^2)	Unit Shaft Resistance Ratio*
Plain w/o P.I.**	P1	764	41	1.0	1.48	1.0
Plain w/ P.I.	P2	948	38	1.14	1.99	1.34
J Company 7% w/o P.I.	P3	764	40	1.0	1.52	1.03
J Company 7% w/ P.I.	P4	948	38.5	1.14	1.96	1.32
D Company 11% w/o P.I.	P5	764	38	1.0	1.60	1.08
D Company 11% w/ P.I.	P6	948	38	1.13	1.99	1.34
D Company 13% w/o P.I.	P7	948	41	1.0	1.84	1.24
D Company 13% w/ P.I.	P8	1040	39	1.14	2.12	1.43
D Company 15% w/ P.I.	P9	1133	39	1.14	2.31	1.56

*Unit Shaft Resistance Ratio = ((f_s of a pile)/(f_s of P1 Pile))

** P.I. = pressurized injection

Table 6. Load test results(without chamber pressure)

Pile Type	Pile Symbol	Ultimate Load (kg)	Pile Length (cm)	GF	Unit Shaft Resistance (kg/cm^2)	Unit Shaft Resistance Ratio*	
						(1)	(2)
Plain w/o P.I.**	P10	579	39	1.0	1.18	1.0	0.80
D Company 13% w/ P.I.	P11	671	40	1.0	1.33	1.13	0.72
D Company 13% w/ P.I.	P12	948	40.5	1.14	1.86	1.58	0.88

*(1) : ((f_s of a pile)/(f_s of P1 pile))

(2) : ((f_s of a pile w/o chamber pressure)(f_s of a pile w/ chamber pressure))

** P.I. = pressurized injection

5.1.1 Influence of Expansive Mortar

The variation of frictional resistance due to expansive agent is described in Table 5. Within the range of mixing ratio tested in this study, piles of expansive mortar without pressurized injection showed a maximum increase in shaft resistance of 24%, while pressurized injection showed a 56% maximum increase on comparison with the shaft resistance of plain mortar without pressurized injection.

As shown in Fig. 7, although piles installed under the same injection methods generally show similar initial slopes in the load-displacement curve, model piles P4 and P5 show a small deviation from the curves of each group. Another notable aspect that can be observed from Fig. 7 is the sudden increase of displacement of test pile P9, which occurred at a load of 770kg. After recovery and inspection of the pile following the test, a tensile crack at roughly one third of the length of the pile starting from the pile tip was discovered, which would explain this behavior.

The variation of the unit shaft friction with various mixing ratios of expansive mortar is shown in Fig. 8. On comparison of the shaft resistance of the piles with regard to the injection process, it can be observed that test piles P3, P4, P5, and P6 whose mixing ratios are smaller than 11% show only a nominal increase in unit shaft resistance. Therefore, it is preliminarily concluded that the optimum mixing ratio of expansive agent lies between 11%~15%, considering the increase of shaft friction with the accompanying reduction of concrete strength.

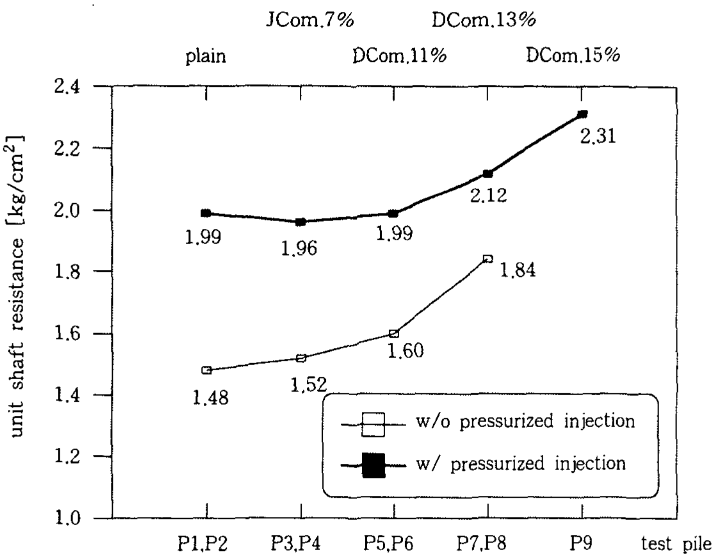

Fig 8. Variation of unit shaft resistance with mixing ratio of expansive mortar(with chamber pressure)

5.1.2 Influence of Pressurized Injection

As shown in Fig. 7 and Table 5, load tests on four couples of piles at different mixing ratios were performed to study the effect of the injection process on frictional resistance. From Fig. 7, it is evident that the initial slope of the load-displacement curves for piles installed with pressurized injection is generally greater, that is stiffer, than that for piles without pressurized injection.

Fig. 9 shows the ratio of unit shaft resistance of piles with pressurized injection to that of piles without pressurized injection for the same mixing ratios of expansive agent. From this comparison, it can be seen that the shaft resistance of piles with pressurized injection increases about 15~34%, compared with that of piles without pressurized injection, and that the degree of improvement in unit shaft resistance due to expansive agent decreases with the increase of the mixing ratio.

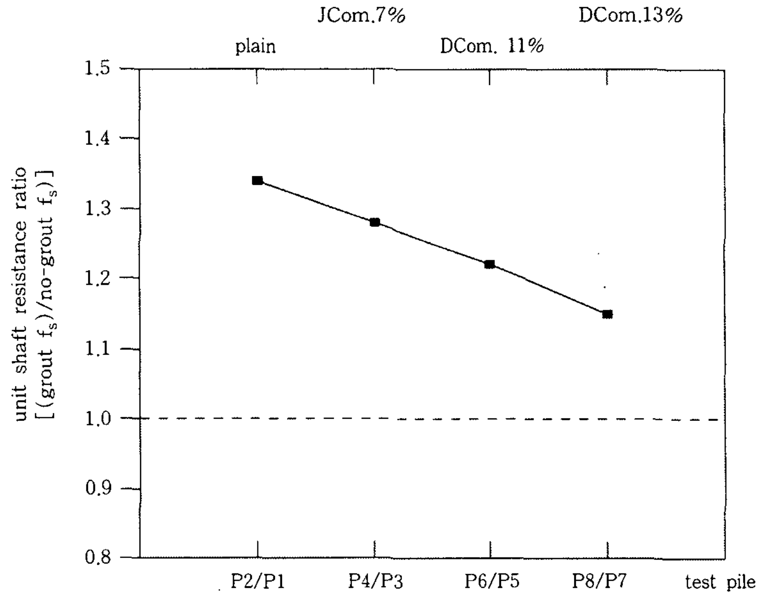

Fig 9. Comparison of relative unit shaft resistance due to pressurized injection(with chamber pressure)

5.2 Load Transfer Test Results

Tensile load tests of two piles(P7 and P8) with attached strain gauges were performed to study the distribution of frictional resistance along the shaft of piles installed using expansive mortar. Seven strain gauges per pile were located 5cm apart along the length of the pile, though one gauge for P7 and three for P8 were found broken during pile installation.

Load transfer curves for P7 and P8 are shown in Fig. 10 and Fig. 12, respectively, and the distribution of the calculated unit shaft friction from the data obtained from the strain gages is illustrated in Fig. 11 and Fig. 13. It can be concluded from the aforementioned figures that the distribution of unit shaft resistance of test pile P8 constructed with pressurized injection was more or less uniform along the length of the pile, while the distribution of test pile P7 without pressurized injection showed a significant variation of unit shaft friction along the pile. Nonuniform distribution of shaft friction along P7 appears to be caused by the inconsistent installation procedure during pouring of the mortar. From Fig. 11 and Fig. 13, it is apparent that the unit shaft resistance at shallow depths(0~5cm) is larger than that of deeper depths, which is most likely due to the confinement of the surface layer by the upper plate of the calibration chamber.

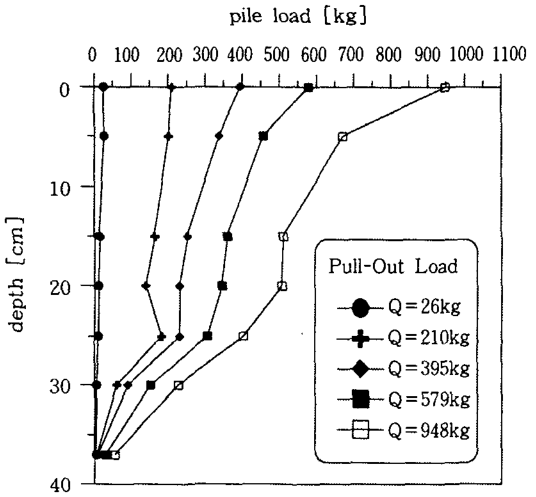

Fig 10. Distribution of axial load of test pile P7

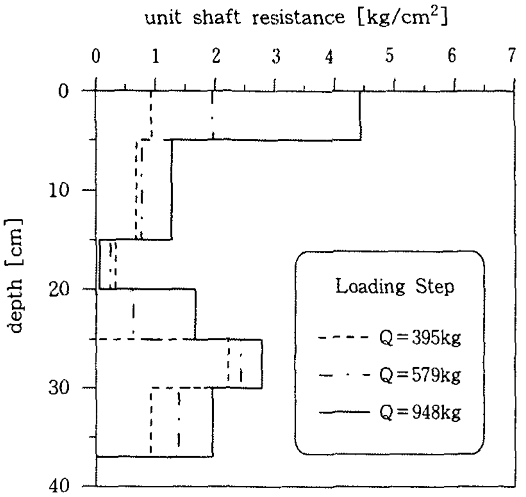

Fig 11. Unit shaft resistance diagram of test pile P7

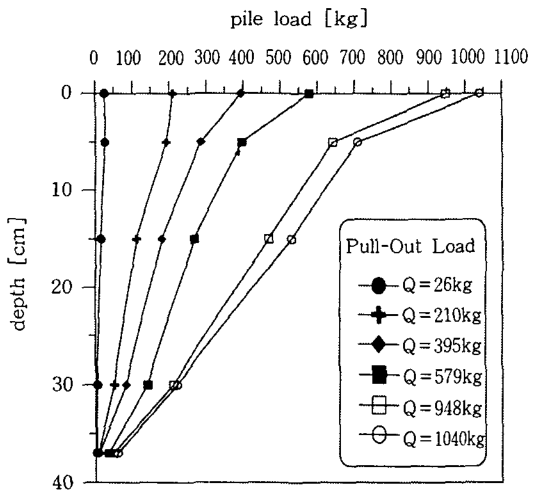

Fig 12. Distribution of axial load of test pile P8

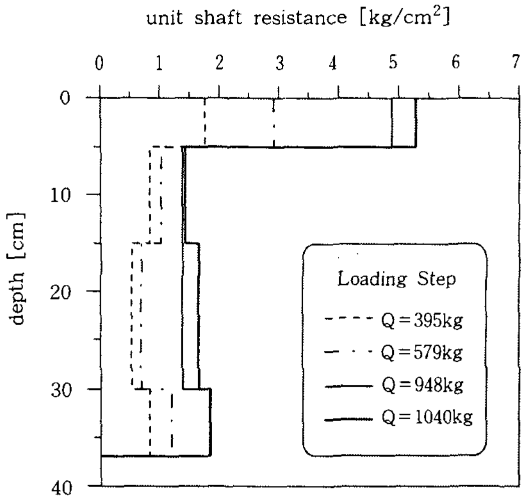

Fig 13. Unit shaft resistance diagram of test pile P8

6. Conclusions

From the pile load tests on the model piles constructed with expansive mortar in the calibration chamber, the following conclusions have been derived.

1. In the case of auger-cast piles having a low shaft resistance due to the disturbance of the soil surrounding the pile, the use of expansive mortar improved the shaft resistance through the increase of contact pressure between soil and pile induced by expansion. However, since the effects of expansive mortar on the shaft resistance may be sensitive to the ground conditions and the degree of disturbance, a suitable mixing ratio must be selected through various in-situ tests for a successful increase in bearing capacity.
2. The shaft resistance of a pile with only 13% expansive mortar and a pile with 13% expansive mortar combined with pressurized injection showed an increase in shaft friction of approximately 24% and 43%, respectively, compared with that of a pile with plain mortar without pressurized injection. For a pile with 15% expansive mortar and pressurized injection combined, the shaft resistance increased by about 56%. It appears that application of both expansive mortar and pressurized injection in unison significantly improves the shaft resistance.
3. As shown in Fig. 8, test piles installed using expansive mortar whose mixing ratios were less than 11% showed only a nominal increase in unit shaft resistance. Considering both the increase of shaft resistance and the reduction of concrete strength due to the expansive agent, it is concluded that the optimum mixing ratio is between 11~15%.

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