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Research of Characteristics of Deep Cement Mixing Columns in Treatment of Soft Soil

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Abstract **- The article presents the content assessment of the application of deep cement mixing technology. From laboratory and field experiments with geological conditions in Duyen Hai - Tra Vinh areas, Vietnam, we will find out the factors that affect the quality and durability of the deep cement mixing column. At the same time, we can determine the optimal ratio about content of cement and water for soil samples after being reinforced to meet the economic - technical requirements. Finally, test data is analysed to serve calculations and simulation based on linear regression models of Microsoft Excel.**

Keywords- Deep cement mixing columns, soft soil, optimal ratio of water and cement, linear regression models.

I. INTRODUCTION

Deep cement mixing columns (DCMCs) are the soil at the construction site and the cement is grouted to the ground by the injection grouting pump. The drill bit is drilled down for loosening the soil until it reaches the depth of the soil layer, that needs to be reinforced, then it comes back and moves up. In the process of moving up, cement is grouted into the ground. This is a new technology applied in flooded areas where other types of columns do not meet the requirements.

DCMCs are widely applied in the treatment of foundation and soft ground for public construction works such as bridges, ports, embankments, repairing the leaking for the sewer sides and sewer bottoms, retaining walls, reinforcing the soil around the tunnel, preventing landslide of the slope, strengthening the roadbed, bridge abutments, etc. Especially in the Mekong Delta, DCMCs are frequently used because this area is often flooded due to high tides and climate change.

With specific advantages in soft ground treatment, the technology of deep cement mixing column is widely used to reinforce the ground, control the subsidence when the work is put into use. The calculation for design of the ground reinforced by the method of DCMCs is based on many different points of view and assumptions.

However, based on the specific conditions of soft soil, topography, geological conditions, construction methods, working conditions of DCMCs and experience, the most appropriate calculation method is chosen.

In addition, the theory of calculating DCMCs is quite limited, when parameters of durability of the pile are used in calculation, they need to be experimented with each specific soil and construction.

II. RESEARCH METHODS

Empirical method: Performing experiments in the laboratory and on the site to determine the specific characteristics and factors affecting the durability and quality of DCMCs.

Theoretical method: Summarizing and selecting experimental data based on linear regression model.

III. TESTING METHODS FOR DETERMINING CHARACTERISTICS OF DCMCs

A. Parameters of soil and materials used for the experiment

Samples of soil ground used in the experiment were taken in the field of Duyen Hai Thermal Power Plant, Duyen Hai District, Tra Vinh Province, Vietnam which all have the same characteristics of soft grey brown clay silt. Samples are taken in the field and carefully stored to ensure the natural criteria for the experiment. Parameters of ground soil and materials used for the experiment are synthesized in Tables I-IV.

TABLE I. PHYSICAL-MECHANICAL PARAMETERS OF SOIL

Parameter	Unit	The average value
Moisture W	%	41.6
Unit weight γ	kN/m^3	17.36
Void ratio e	-	1.123
Cohesive force C	kN/m^2	7.4
Angle of internal friction φ	Degree	1.74
Plastic limit W_P	%	22.92
Liquid limit W_L	%	39.99
Plasticity index I_P	%	17.07
Liquidity index I_L	-	1.1

TABLE II. PHYSICAL-MECHANICAL PARAMETERS OF CEMENT

Parameter	Unit	Standard (TCVN)	Limit	Sample test results
Specific weight	kN/m^3	4030-2003	-	29.6
Volumetric mass	kN/m^3	1772-87	-	1.21
Standard consistency	%	6017-1995	-	26
Time to start setting	minute	6017-1995	> 45	115
Time to end setting	minute	6017-1995	< 420	320
Volumetric stability	mm	6017-1995	< 10	2.33
Fineness of grinding of the remainder on the 0.09mm sieve	%	4030-2003	< 10	1.5
Bending strength at 28 days	kN/m^2	6017-1995	-	9.75
Compressive strength at 28 days	kN/m^2	6017-1995	≥ 40	42.9

TABLE III. PHYSICAL-MECHANICAL PARAMETERS OF DOMESTIC WATER USED FOR SAMPLE PREPARATION

Determination parameter	**Unit**	**Water used to prepare the samples**	
		Result	**TCVN 302-2004**
Color	Level	Colorless	Colorless
Greasy scum	Level	No scum	No scum
pH	Degree	7.4	4÷12.5
Total amount of dissolved salt	mg/L	9.2	≤ 200
Content of $(SO_4)^{2-}$	mg/L	23.5	≤ 600
Content of Cl^-	mg/L	52.6	≤ 350
Total amount of suspended solid (SS)	mg/L	25	≤ 200

TABLE IV. PHYSICAL-MECHANICAL PARAMETERS OF WATER AT THE SAMPLING LOCATION USED FOR SAMPLE PREPARATION

Parameter	**Unit**	**Water at the sampling location**	
		Amount	**According to TCXD 3994-1985**
Temperature	^0C	28.125	
pH	-	7.885	
Clearness	Sensing	Turbid	
Odor	Sensing	Non	
Free CO_2	mg/L	12.194	No corrosion
Corrosive CO_2	mg/L	0	
$Na^+ + K^+$	mg/L	9109.644	
Ca^{2+}	mg/L	285.82	
Mg^{2+}	mg/L	863.208	No corrosion
Cl^-	mg/L	15575.86	
$(SO_4)^{2-}$	mg/L	1772.608	Strong corrosion
$(HCO_3)^-$	mg/L	318.066	
$(CO_3)^{2-}$	mg/L	0.75	
Total hardness	mg/L	85.25	
Total mineralization	mg/L	27927.95	Medium corrosion

B. Uniaxial unconfined compression test

B.1. Experimental results for mixing samples using domestic water with a ratio of water / cement respectively as 1.4; 1.0; 0.8

a) Experiment 1: Water/Cement =1.4

- Based on Fig. 1, we can see that the value of qu (kPa) from 7 to 14 days of age increases rapidly by about 70 times compared to the original soil without reinforcement, then it tends to increase slowly until 28 days of age.

- The intensity of deep cement mixing sample is proportional to the amount of cement in preparation. But when the amount of cement quickly grows from 14% to 20%, the intensity of cement tends to increase slowly. (Table V)

TABLE V. UNIAXIAL COMPRESSIVE STRENGTH QU FOR MIXING SAMPLE USING DOMESTIC WATER WITH THE RATIO OF W/C =1.4

Day	**Uniaxial compressive strength q_u (kPa)**					
	M100 (6%)	M150 (9%)	M200 (12%)	M250 (14%)	M300 (17%)	M350 (20%)
0	15	15	15	15	15	15
7	218.3	533.3	687.3	790.2	914.3	1206.7
14	293.4	702.6	1068.1	1226.8	1376.3	1609.1
28	322.2	943.9	1339.9	1687.7	1779.5	1960.4

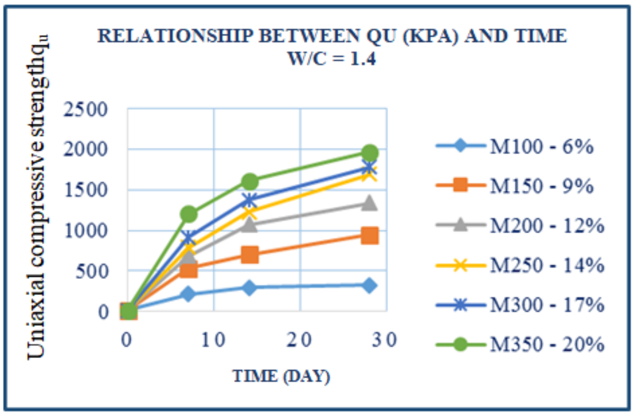

Fig. 1. Uniaxial compressive strength of experiment 1

b) Experiment 2: Water/Cement =1.0

Uniaxial compressive strength q_u for mixing sample using domestic water with the ratio of W/C=1 is synthesized in Table VI.

TABLE VI. UNIAXIAL COMPRESSIVE STRENGTH QU FOR MIXING SAMPLE USING DOMESTIC WATER WITH THE RATIO OF W/C=1

Day	**Uniaxial compressive strength q_u (kPa)**					
	M100 (6%)	M150 (9%)	M200 (12%)	M250 (14%)	M300 (17%)	M350 (20%)
0	15	15	15	15	15	15
7	284	569.7	982.4	1097.9	1447.3	1818.5
14	421.5	957	1394.5	1618.2	1959.2	2360.4
28	554.1	1365	2076.7	2247	2736.5	3389.8

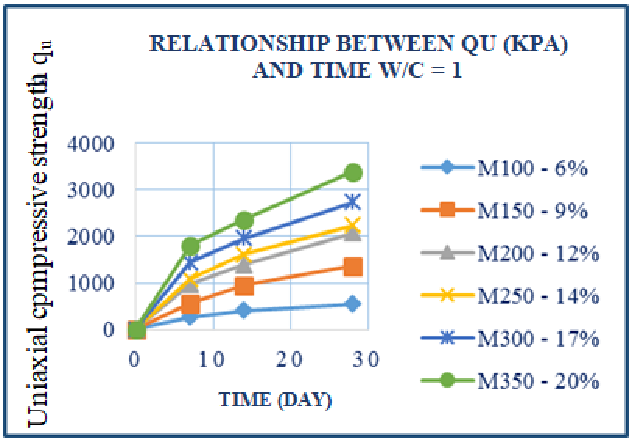

Fig. 2. Uniaxial compressive strength of experiment 2

The result in Fig.2 indicates that the value of q_u (kPa) in this experiment increases more strongly compared to that of experiment 1, specifically at 28 days of age the value of q_u (kPa) increases by about 137 times in comparison with that at 28 days of age after being reinforced. The main reason is due to the change of the water amount when mixing sample. Compared with experiment 1, in this experiment, when the water amount decreases by 40% when mixing, the value of q_u (kPa) of the sample will increase by 55.24% at 28 days of age.

c) Experiment 3: Water/Cement = 0.8

Uniaxial compressive strength q_u for mixing sample using domestic water with the ratio of W/C= 0.8 is synthesized in Table VII.

TABLE VII. UNIAXIAL COMPRESSIVE STRENGTH QU FOR MIXING SAMPLE USING DOMESTIC WATER WITH THE RATIO OF W/C=0.8

Day	**Uniaxial compressive strength q_u (kPa)**					
	M100 (6%)	M150 (9%)	M200 (12%)	M250 (14%)	M300 (17%)	M350 (20%)
0	15	15	15	15	15	15
7	394.592	777.7	1518.9	1725.4	2107.4	285.1
14	605.706	1313.3	2381	2582.07	2974.3	4099.6
28	838.157	1720.1	2644.3	3493.06	4448.9	25866.3

Based on Fig. 3, it is said that the value of q_u (kPa) of deep cement mixing sample in this experiment increases more significantly than those of experiments 1 and 2. The uniaxial compressive strength of natural soil increases about 211 times at 28 days of age after being reinforced. Similar to the first two experiments, when we perform the experiment of changing the ratio of water/ cement on preparing the sample, it will significantly change the value of q_u (kPa) of DCMCs.

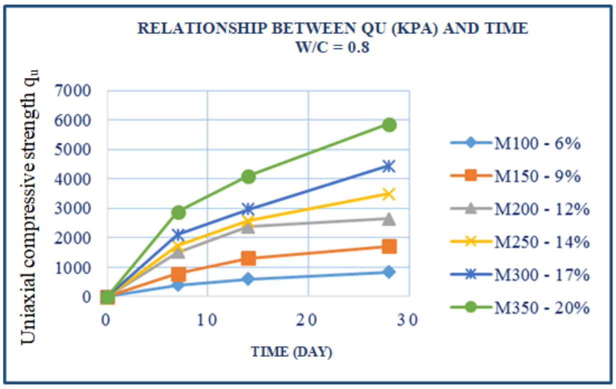

Fig. 3. Uniaxial compressive strength of experiment 3

B.2. Experimental results for mixing samples using water at the sampling location with a ratio of water/cement = 1.0

Experiment 4: W/C=1 (water at the sampling location)

TABLE VIII. UNIAXIAL COMPRESSIVE STRENGTH QU FOR MIXING SAMPLE USING WATER AT THE SAMPLING LOCATION WITH THE RATIO OF W/C=1

Day	**Uniaxial compressive strength q_u (kPa)**					
	M100 (6%)	M150 (9%)	M200 (12%)	M250 (14%)	M300 (17%)	M350 (20%)
0	15	15	15	15	15	15
7	159.992	259.296	505.251	562.143	903.598	1091.86
14	216.238	400.343	871.621	1509.04	1645.84	1896.05
28	304.228	574.236	1271.21	1613.32	2121.56	2432.66

- Compared to experiments 1, 2, 3 (W/C = 1.4; 1; 0.8), in this experiment 4, based on Fig. 4, we find that the value of qu (kPa) at 28 days of age is quite low, it declines about 36.79% compared to experiment 1 (W/C = 1), 57.82% compared to experiment 2 (W/C = 0.8) and 1.83% lower than experiment 3 with a W/C ratio of 1.4.

The main reason is that the water for mixing sample has too high acid content which is shown in [Table IV] then, it facilitates the process of chloride corrosion and sulfate attacking, resulting in the formation of ettringite (sulfoaluminatehydrate: $3CaO.Al_2O_3.3CaSO_4.32H_2O$) and gypsum ($CaSO_4.2H_2O$) softening of cement paste, changing the microstructure to increase porosity and reduce the strength of the deep cement mixing pile.

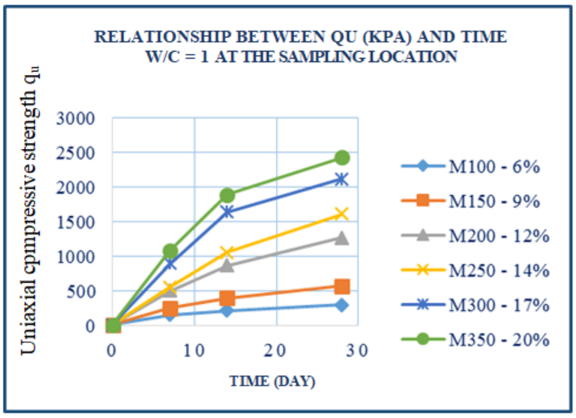

Fig. 4. Uniaxial compressive strength of experiment 4

C. Comparison of laboratory experimental results

Based on Fig. 5, we see that experiments with the same type of water [Table III] and cement but with different mixing rates, the results are quite different. Water quality has a great influence on the strength and quality of DCMCs, so it is impossible to reinforce the soft soil in this area by dry mixing technology.

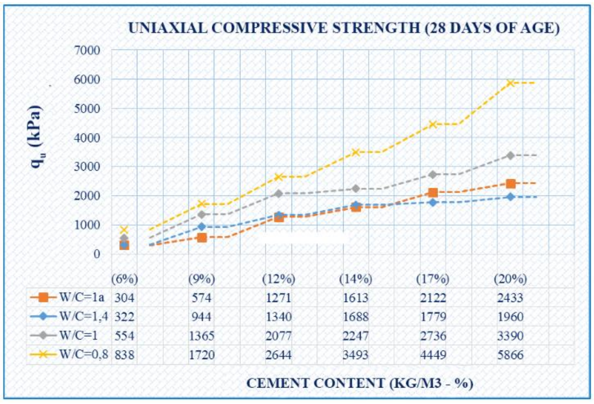

Fig. 5. Uniaxial compressive strength qu of 4 experiments in laboratory

D. Comparison with field experimental results

Based on the results of 4 experiments in laboratory, the ratio W/C = 0.8 and the cement content of 14% will be the optimal content for mass construction. To verify the feasibility of this option, the comparison with the field results is implemented as Fig. 6.

Fig. 6. Comparision of the value of qu (kPa) between lab and field experiments

When the cement content is 14%, we see that the result of compressing samples in the field gives higher values than those of experiments in laboratory when the ratio of W/C = 1.4 and W/C = 1. With this content, the value of q_u (kPa) of the field results is quite high but about 35.5% lower than that in the laboratory because the condition of sample preparation in the laboratory is almost ideal. Results of compression in the field also depend on: Modernity and accuracy of the mechanical system, geological conditions around the reinforced area, construction techniques, etc.

E. Direct shear test

Using the optimal content to determine 02 basic characteristics of shear resistance as Table IX.

TABLE IX. ANGLE OF INTERNAL FRICTION VALUE FROM DIRECT SHEAR TEST

Day	Angle of internal friction φ (degree)					
	6%	9%	12%	14%	17%	20%
0	1.74	1.74	1.74	1.74	1.74	1.74
7	21.8	20.22	11.73	14.01	14.44	15.63
14	20.53	17.34	14.76	12.98	12.05	10.86
28	17.13	14.63	12.34	8.61	7.21	11.09

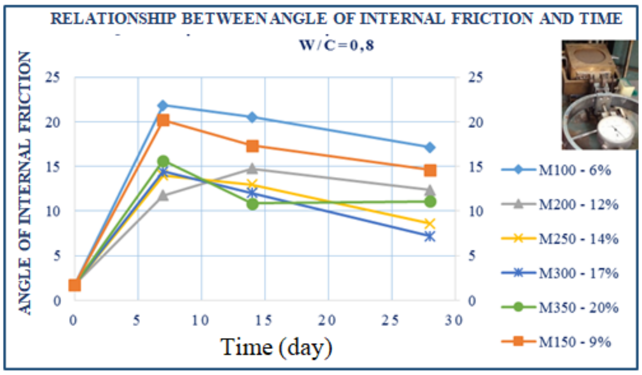

Fig. 7. Experimental results and relation between φ (degree) and time

TABLE X. COHESIVE FORCE C FROM DIRECT SHEAR TEST

Day	Angle of internal friction φ (degree)					
	6%	9%	12%	14%	17%	20%
0	7.4	7.4	7.4	7.4	7.4	7.4
7	49.06	75.145	228.31	239.41	241.51	267.05
14	93.218	154.435	267.506	297.678	325.509	339.524
28	116.89	208.979	316.207	448.162	450.336	457.167

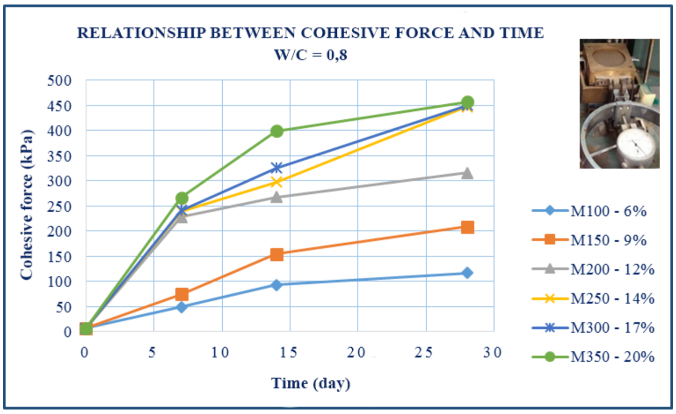

Fig. 8. Experimental results and relation between C (kPa) and time

Fig. 8 indicates that: At the time of 28 days of age, the cohesive force value of the sample at the rate of 6-12% is relatively small, but for the ratio of 14-20%, the value is nearly converged and it is not much different, with the average of about 451.89 (kPa). This also confirms that the optimal content selected for mass construction is reasonable, meeting economic - technical requirements when investment of the work. The correlation of φ (degree) and C (kPa) at 28 days of age is quite close with coefficient R^2 = 0.8753 and they are inversely proportional when the content of cement increases.

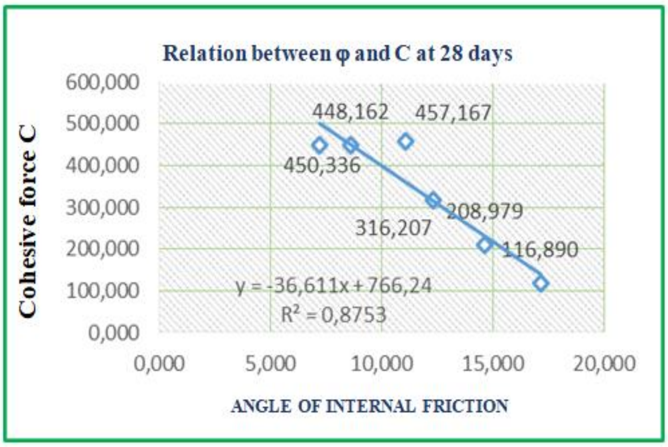

Fig. 9. Relation between φ (degree) and C (kPa) at 28 days

F. Analyzing experimental data, select results according to linear regression model

Determination of value of q_u (kPa) and summary of results of experiment 3 at 28 days of age are shown in table XI.

TABEL XI. SUMMARY OF RESULTS OF UNIAXIAL COMPRESSION TEST

Content	X_1 Weight (g)	X_2 Diameter D (mm)	X_3 Height H (mm)	X_4 (H/D)	X_5 Volumetric weight (g/cm³)	X_6 Compression deformation (mm)	X_7 Axial deformation (mm)	X_8 S_0 (mm²)	X_9 S_i (mm²)	X_{10} Moisture (%)	X_{11} Collapse angle (degree)	X_{12} Maximum load (N)
6% W/C = 0.8	299	46	99	2.15	1.817	1.6	0.0162	1661.9	1689.27	0.3188	33	1417
	298	46.3	99	2.14	1.788	1.5	0.0152	1683.65	1709.64	0.3255	35	1302
	303	45.3	101	2.23	1.861	1.4	0.0139	1611.71	1634.43	0.3582	22	1494
9% W/C = 0.8	302	45.5	98.1	2.16	1.893	1.3	0.0133	1625.97	1647.89	0.2837	30	3187
	294	45.2	96	2.12	1.909	1.2	0.0125	1604.6	1624.91	0.2755	27	2728
	303	45	99.2	2.2	1.921	1	0.0101	1590.43	1606.66	0.3015	20	2486
12% W/C = 0.8	306	45.8	104	2.27	1.786	1.3	0.0125	1647.48	1668.34	0.2783	30	4246
	307	45.8	98.8	2.16	1.886	1.5	0.0152	1647.48	1672.91	0.2782	29	5164
	303	45	99	2.2	1.924	1.5	0.0152	1590.43	1614.98	0.2784	23	3716
14% W/C = 0.8	306	45.9	99	2.16	1.868	1.5	0.0152	1654.69	1680.22	0.2758	29	
	294	45.1	98.3	2.18	1.872	1.6	0.0163	1597.51	1623.98	0.2746	35	55626056
	302	45.2	98.6	2.18	1.909	1.6	0.0162	1604.6	1631.02	0.277	35	5435
17% W/C = 0.8	302	46	97	2.11	1.873	1.7	0.0175	1661.9	1961.5	0.27	34	7302
	305	45.5	98.1	2.16	1.912	1.8	0.0183	1625.97	1656.28	0.2639	32	7079
	306	45.7	98.3	2.15	1.898	1.8	0.0183	1640.3	1670.87	0.2761	30	7946
20% W/C = 0.8	09	45.8	98.9	2.16	1.896	2.3	0.0233	1647.48	1686.79	0.2615	30	10136
	302	45.6	96.5	2.12	1.916	2	0.0207	1633.13	1667.65	0.2609	20	8781
	302	45.3	99.3	2.19	1.887	2.3	0.0232	1611.71	1649.99	0.2622	30	10435

The regression equation is as equation (1).

$$-(34.346\, X_1) - (3550.21\, X_2) + (116.92\, X_3) - (526.02\, X_4) + (5531.98\, X_5) - (188.01\, X_6) + (325201.76\, X_7) + (237.94\, X_8) - (181.18\, X_9) - (32.86\, X_{10}) + (1.14\, X_{11}) + (0.6\, X_{12}) + 58687.13 = q_{ui}\ (\text{kPa}) \quad (1)$$

Value of q_u = 3491.90 (kPa) is found through the regression equation with the cement content of 14% (W/C=0.8).

With R^2= 0.99996.

As table XII, the regression equation is as follows:

$$-(68.32\, X_1) + (0\, X_2) + (0\, X_3) + (0\, X_4) + (4132.37\, X_5) + (81.75\, X_6) - (449.7\, X_7) + (12.39\, X_8) + (6.94\, X_9) - 57.3 = \tau_i\ (\text{kPa}) \quad (2)$$

The value of internal friction angle φ (degree) and cohesive force C (kPa) found through the regression equation with the cement content of 14% (W/C=0.8) are φ = 8.80 (degree) and C= 437.10 (kPa), respectively. With R^2= 0.995995.

TABLE XII. SUMMARY OF RESULTS OF DIRECT SHEAR TEST

Content	X_1 Weight (g)	X_2 Diameter D (mm)	X_3 Height H (mm)	X_4 (H/D)	X_5 Volumetric weight (g/cm³)	X_6 Moisture (%)	X_7 Load level (kg)	X_8 Adjusted pressure (kPa)	X_9 Data of meter
6% W/C = 0.8		62	20	0.32	0.893	0.3188	2	73	25
		62	20	0.32	0.952	0.3255	4	146	28
		62	20	0.32	1.882	0.3582	8	291	41
9% W/C = 0.8		62	20	0.32	1.89	0.2837	2	73	44
		62	20	0.32	1.881	0.2755	4	146	51
		62	20	0.32	1.86	0.3015	8	291	63
12% W/C = 0.8		62	20	0.32	1.916	0.2783	2	73	51
		62	20	0.32	1.873	0.2782	4	146	65
		62	20	0.32	1.89	0.2784	8	291	75
14% W/C = 0.8		62	20	0.32	1.888	0.2758	2	73	70
		62	20	0.32	1.897	0.2746	4	146	83
		62	20	0.32	1.911	0.277	8	291	92
17% W/C = 0.8		62	20	0.32	1.889	0.27	2	73	72
		62	20	0.32	1.865	0.2639	4	146	76
		62	20	0.32	1.887	0.2761	8	291	88
20% W/C = 0.8	112.3	62	20	0.32	1.86	0.2615	2	73	77
	114.1	62	20	0.32	1.889	0.2609	4	146	95
	108	62	20	0.32	1.788	0.2622	8	291	114

Comment: Selecting data using a linear regression model find that the typical values of DCMCs are 0.03% lower than the average value, at the same time, correlation coefficient R value is very high, approximately equal to 1, indicating that the relationship of the quantities and results is very close, the error during the experiment is low.

4. CONCLUSIONS

When reinforcing soft soil ground in coastal area of Vietnam, in the Southwest region in general and in Duyen Hai - Tra Vinh area in particular by deep cement mixing technology, it should be chosen with the ratio of W/C = 0.6 - 0.8, cement content of 14 - 16% (equivalent to 250 - 270 kg cement/m^3 of natural soil), this will significantly improve the bearing capacity of soil up to hundreds of times. With the optimal ratio above, the compression result in the field gives quite high results, controlling the product quality and furthermore, ensuring economic - technical requirements.

The content and quality of water when mixing samples is one of the main factors that determine the quality and durability of deep cement mixing pillar.

Using a linear regression model based on Data Analysis application of Microsoft Excel software is very useful. This tool helps us re-test the experiment process, limit errors and at the same time increase the reliability of scientific products.

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