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TECHNICAL NOTE

Assessment of strength development in cement-admixed high water content clays with Abrams' law as a basis

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KEYWORDS: clays; ground improvement

INTRODUCTION

Composite soft ground formation with columnar inclusions by in-situ deep mixing or jet grouting is extensively used to mitigate the adverse effects of low bearing capacity and high compressibility of soft clay ground (e.g. Kawasaki *et al.*, 1981; Terashi & Tanaka, 1981; Kamon & Bergado, 1992; Kamaluddin & Balasubramaniam, 1995; Yin & Lai, 1998). In general, many laboratory trials are needed for determination of strength before the execution of soil–cement columns. In order to minimise the number of trials needed to arrive at the quantity of cement to be admixed, it is desirable to have a simple method to predict strength development with time for various combinations of clay water content and cement content. This technical note presents such a method based on Abrams' law, which is extensively used in concrete technology.

CEMENT-ADMIXED SOFT CLAYS: MATERIAL CHARACTERISTICS AND INTERACTIONS

Cement and clays are particulate materials that interact with water by virtue of their reactivity. As cement is the only interacting material in cement-based composites, it is the hardened cement paste that provides the continuity in structure with the coarse constituents in embedded state. In the case of soft clays, because of physico-chemical interactions with water the clay is an engineering material with an effective stress that corresponds to non-zero matrix suction (Nagaraj *et al.*, 1994; Nagaraj & Miura, 2001). If a cementing agent is admixed with such a system, the strength increases over time as the clay reduces to the non-particulate state as a result of cementation.

Extensive earlier research (Nagaraj *et al.*, 1990; Yamadera, 1999; Nagaraj & Miura, 2001) has revealed that the microfabric of clay consists of an aggregation of clay particles and enclosed capillary pores, as shown in Fig. 1(a).

Investigation and analysis of the compressibility and permeability of clays, in both their uncemented and cemented states, along with pore size distribution data (Nagaraj *et al.*, 1995; Yamadera *et al.*, 1998) (Figs 2 and 3) leads us to the following conclusions:

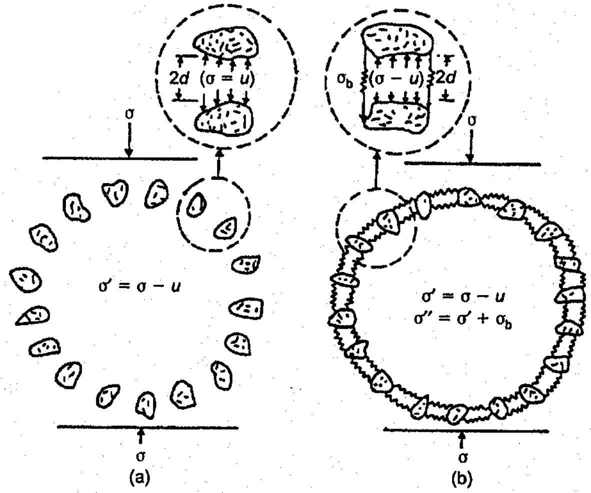

Fig. 1. Microfabric of clay: (a) microfabric; (b) structure of the same clay

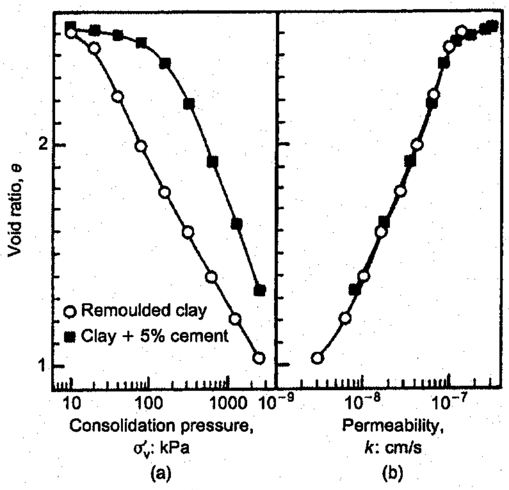

Fig. 2. (a) void ratio against consolidation pressure; (b) void ratio against permeability of remoulded and cemented Ariake clay (Yamedara *et al.*, 1998).

(*a*) Cemented clays exhibit the same order of permeability as that of uncemented clays at the same void ratio, which suggests that the microfabric is of the same pattern.

(*b*) The role of the induced cementation is to weld the fabric (Fig. 1(b)).

(*c*) The shear strength and resistance to compression increase with rest period owing to the enhancement of bonding for the same level of cementing agents.

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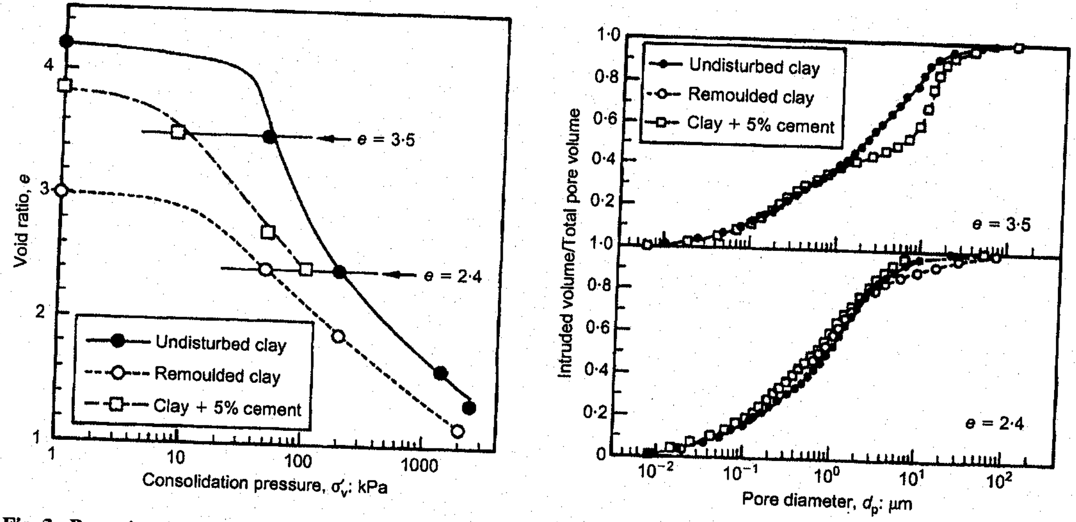

Fig. 3. Pore size distribution in Ariake clay at same void ratios in undisturbed, remoulded and cemented states (Yamedera *et al.*, 1998)

Cement-based composites show a continuity in the structure of the hardened paste, with fine and coarse aggregates embedded in it. In the case of soft clays, however, cement is added to a system with a preformed fabric. The role of cement here is to strengthen the fabric at the intercluster spacing: that is, to weld the fabric at these sites as shown in Fig. 1(b). In the case of soft clays, water is already present (or increases owing to the cement admixture): it is not free, but it is able to interact with the clay. Hence the clay-water/cement ratio, w_c/C (where both are expressed in percent), is a more appropriate parameter than water–cement ratio, w/c in the analysis of the strength development of cement-admixed soft clays.

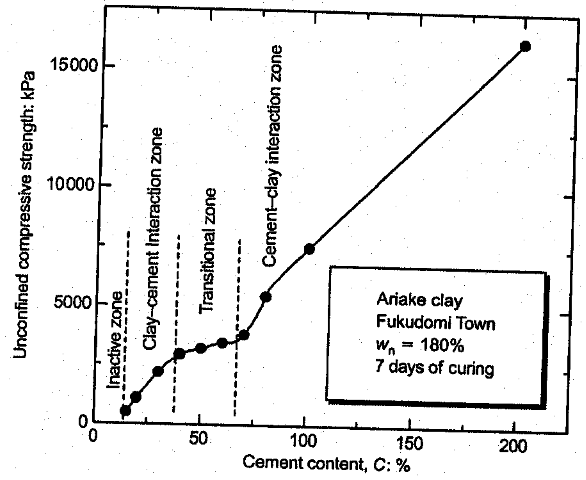

Fig. 4. Clay–cement and cement–clay interaction zones

EXPERIMENTAL DETAILS

The clay samples used in these investigations are from Fukodomi (w_L = 120%, w_P = 57%) and Nishiyoka (w_L = 120%, w_P = 57%) of Saga Prefecture, Japan. The natural water content of these clays is higher than their respective liquid limit water content. The clay paste was passed through a 2 mm sieve for removal of shell pieces, adjusted to different water contents at different levels of liquidity indices, and admixed with ordinary Portland cement at different percentages by weight of dry clay in the mix. Split moulds were used for cylindrical samples and left for different periods of curing. The unconfined compressive strength was determined as an index to measure the improvement in strength. The compressive strength increased as the cement content increased from 5% to 25%. According to Uddin (1994) strength increases only marginally at cement contents lower than 5%.

In order to cover the entire range of cement admixtures, for the Ariake clay from Fukudomi town, the admixed cement percentage was varied over a wide range up to 200%. Fig. 4 shows the unconfined compressive strength plotted against cement content at different levels. It is interesting that, apart from three zones noticed by Uddin (1994), a greater rate of increase in strength with cement content was observed at higher percentages of cement content. This can be explained within the framework of clay fabric and subsequent microstructure formation due to bonding as follows. When the cement content is low, the cement available per intercluster site is too low to bring about any noticeable change in strength. This inactive zone is designated as zone 1. As the cement content increases, the cement content per intercluster site increases and, upon hardening, imparts a commensurate amount of bonding to the clay fabric. This zone is designated as the clay–cement interaction zone (zone 2). There is a limit to the cement content that is effective in inducing cementation bonding. Up to this state, there is continuity in the clay fabric and discontinuity in the hardened structure of the cement paste. There comes a stage at which, as the cement content increases, the clay microstructure loses its identity and the strength increases as the continuity in the hardened cement paste structure prevails, with the clay clusters being embedded in it. This is identified as the cement–clay interaction zone (zone 4). The zone between zones 2 and 4 is zone 3.

Zone 3 is a transitional zone in which the strength increase is marginal and the cement is not utilised fully in strengthening the clay fabric but is insufficient to transform to the stage where the clay fabric loses its identity. In the development of a phenomenological model to assess the strength development, the experimental investigation is limited to zone 2. The cement content is in the range 5–25%.

ANALYSIS OF STRENGTH DEVELOPMENT

As early as 1918 a systematic method of formulating concrete mixtures was published by Abrams (1918). He enunciated the water–cement ratio strength law as follows: 'For a given set of materials, the strength development depends only on one factor, i.e. the ratio of water to cement content in a given mix, with the functional relation being expressed as

$$S = \frac{A}{B^{(w/c)}} \qquad (1)$$

where S is the compressive strength of concrete at a specific age, w/c is the water–cement ratio by weight, and A and B are empirical constants.

The research reported here employs equation (1) to analyse the strength data for two clays at different liquidity indices and rest periods (7, 14 and 28 days). Fig. 5 shows the effect of liquidity index (LI) on the unconfined compressive strength at different rest periods for Ariake clay with variations in the clay-water/cement ratio. Analysis of the data of Uddin (1994) for Bangkok clay at an initial water content of 80% leads to similar results (Fig. 6).

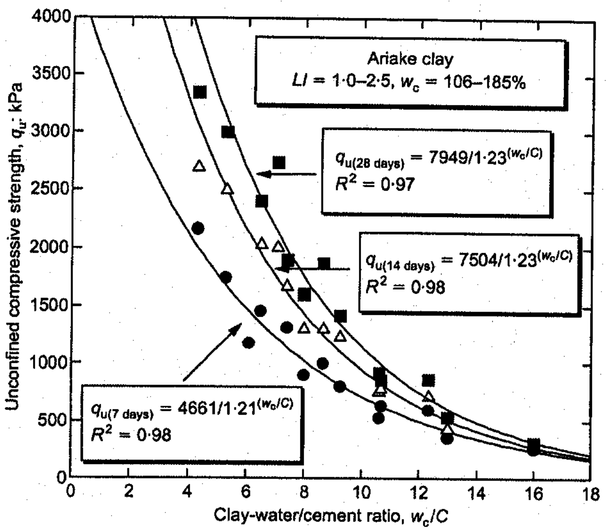

Fig. 5. Variation of strength with clay-water/cement ratio for different rest periods as liquidity index increases, according to Abrams' law

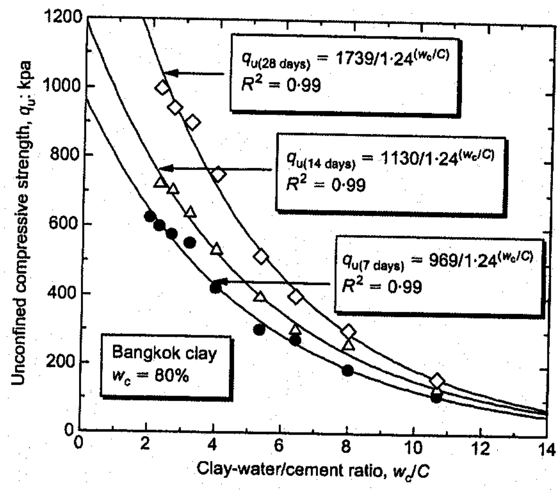

Fig. 6. Variation of strength of Bangkok clay with clay-water/cement ratio for different rest periods at natural water content of 80%, according to Abrams' law

In all the cases the variation of parameter A is marked, and is dependent on the type of clay, the liquidity index and the rest period. However, the variation of parameter B in the liquidity range 1–2·5 is only between 1·22 and 1·24 irrespective of the type of clay or the rest period. These observations suggest that, when formulating a generalised relationship to assess the strength development, it is necessary to eliminate the parameter A. Parameter B can be taken as constant for the range of liquidity indices considered.

While considering the strength ratio of cement-admixed clay, it is possible to eliminate parameter A by taking the ratios of strength developed at different clay-water/cement ratios. This is based on the fact that A has a specific value for a clay at a specified rest period and liquidity index, but does not vary as the clay-water/cement ratio varies. This results in the following relation:

$$\frac{q_{(w_c/C)_1}}{q_{(w_c/C)_2}} = \frac{A/B^{(w_c/C)_1}}{A/B^{(w_c/C)_2}} = 1{\cdot}24^{(w_c/C)_1-(w_c/C)_2} \qquad (2)$$

where $q_{(w_c/C)_1}$ is the strength to be estimated at a clay-water/cement ratio of $(w_c/C)_1$ and $q_{(w_c/C)_2}$ is the strength value at a clay-water/cement ratio of $(w_c/C)_2$. The value of parameter B is taken to be 1·24. The implication of the above relation is that one laboratory test value of strength developed over a specific curing time at any clay-water/cement ratio is needed. From the above equation, it would be possible to assess the strength at any other clay-water/cement ratio.

The limitation of the above relation is that variation in curing time cannot be accounted for directly in strength assessment. The specific question that might arise in practice would be: how far can the curing time can be reduced by an increase in cement content, and vice versa, to obtain the required strength under conditions of clay water content as encountered or altered during cement admixture? To explore the possibility of obtaining more general relationships, the pattern of strength development with time is examined further.

STRENGTH DEVELOPMENT WITH TIME

Figure 7 is a plot of strength development against curing time as observed in an experiment with Ariake clay admixed with cement at liquidity index of 1 and 2. Fig. 8 shows a similar plot prepared for Bangkok clay, taken from Uddin (1994).

These observations and analysis show that, at a particular value of w_c/C, strength development with time is controlled only by the value of A, as B is regarded as constant. As a result, the general relationship between strength development and time can be represented as

$$\frac{q_{D_1}}{q_{D_2}} = \frac{A_{D_1}}{A_{D_2}} \qquad (3)$$

where q_{D_1} is the strength to be estimated at D_1 days of curing, q_{D_2} is the strength value at D_2 days of curing, and A_{D_1} and A_{D_2} are the corresponding values of A.

The differences in the values of A for different clays would be due to variations in the composition of the clay and the pore fluid. However, the rate of strength development with time is identical for various clays, as the hydra-

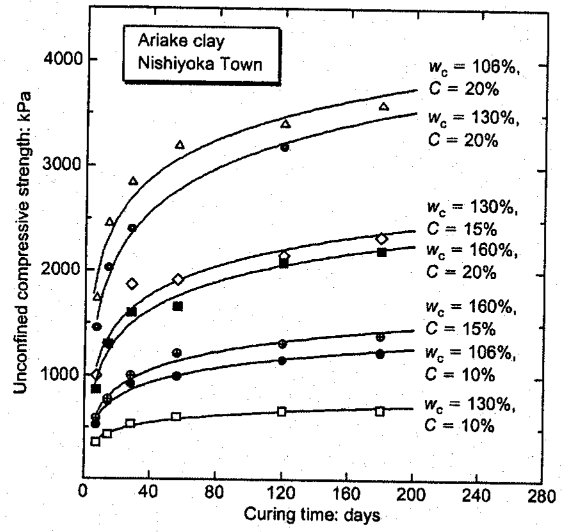

Fig. 7. Strength development with time of cement-admixed Ariake clay from Nishiyoka town at $LI = 1{\cdot}0$–$2{\cdot}0$

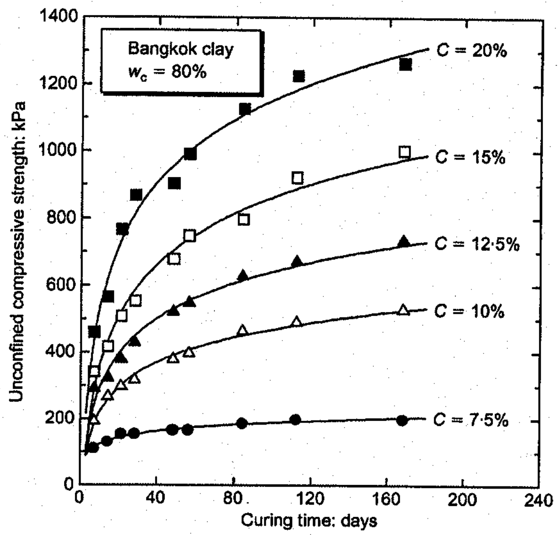

Fig. 8. Strength development with time of cement-admixed Bangkok clay at clay water content of 80%

tion products influence rate significantly. Hence equation (3) represents a unique relationship for a specific clay. In practice, it would be desirable to assess the strength of cement admixed in terms of curing time along with changes in clay-water/cement ratio.

It has been possible to generalise Abrams' law (Nagaraj & Zahida Banu, 1996) by considering the compressive strength of concrete at a water/cement ratio of 0·5 at age 28 days and with $S_{0{\cdot}5}$ as a reference value. The strength ratio $S/S_{0{\cdot}5}$ reflects the microstructure of hardened cement paste at a specific water/cement ratio at a specified age irrespective of the characteristics of the cement. Such an attempt has been made using the 28-day strength as a reference value. By considering the curing time (days) in a natural logarithmic scale the strength variation with age can be expressed as a linear variation. Fig. 9 depicts such linear plots for extensive data experimentally generated in this investigation and collected from other sources. The inland clay data are from Nagaraj *et al.* (1996), and those for Thailand are from Uddin (1994) and Bergado *et al.* (1999). The strength ratio plots after normalisation are shown in Fig. 9, yielding the following relationship:

$$\frac{q_D}{q_{28}} = 0{\cdot}038 + 0{\cdot}281 \ln D \text{ for } LI = 1{\cdot}0\text{–}2{\cdot}5 \tag{4}$$

where q_D is the strength after D days of curing, q_{28} is the 28-day strength, and D is the curing time (days). The normalisation accounts for the effects of difference in clay type, clay water content and cement content.

INTERRELATIONSHIP BETWEEN CLAY-WATER/CEMENT RATIO, CURING TIME AND STRENGTH

The value of B for marine and inland clays at $LI = 1{\cdot}0$–$2{\cdot}5$ is taken to be 1·24. As the strength ratios of cement-admixed marine and inland clays at a particular curing time are being considered, the corresponding values of A cancel out as they are in both the numerator and the denominator. The generalised interrelationship between strength, curing time and w_c/C for predicting strength development of cement-admixed clays for w_c/C ranging from 3 to 16 is expressed by a combination of equations (2) and (4):

$$\frac{q_{(w_c/C)_{1,D}}}{q_{(w_c/C)_{28}}} = 1{\cdot}24^{[(w_c/C)_{28}-(w_c/C)_D]}(0{\cdot}038 + 0{\cdot}281 \ln D) \tag{5}$$

where $q_{(w_c/C)_{1,D}}$ is the strength of cement-admixed clay to be estimated at a clay-water/cement ratio of $(w_c/C)_1$ after D days of curing, and $q_{(w_c/C)_{28}}$ is the strength of cement-stabilised clay at a clay-water/cement ratio (w_c/C) after 28 days of curing. When $(w_c/C)_D = (w_c/C)_{28}$ for $D = 28$ days, the left-hand side of the expressions in equation (5) amounts to unity and the right-hand side to 0·972. This reinforces the application of these relations for different situations. The results of application of the proposed relation to determine the strength development for a clay from Thailand are presented in Table 1. These results were obtained at the Asian Institute of Technology by Soralump (1996) while stabilising soft clay for the Bangana–Bangpakong Highway Project.

The proposed expression is simple within the framework of Abrams' law, and requires strength data for only one trial mix. Other possible combinations can be estimated from the data of the trial mix.

CONCLUDING REMARKS

The phenomenological model proposed here comes within the framework of Abrams' law, which is extensively used in concrete technology. The clay-water/cement ratio, w_c/C, is the appropriate parameter in the analysis of strength development of cement-admixed soft clays because it accounts for the interactions between two particulate materials. Whereas the clay water content reflects the microfabric of soft clay, the cement content influences the level of bonding of that fabric. This relationship, reported in equation (5), is useful in estimating the strength of cement-admixed clay in which the water content and cement content vary over a wide range. Data from a single trial can be extrapolated to a variety of component ratios. The formulation of the presented model is based on sound principles, but the constants need refining/observing from the analysis of more field data.

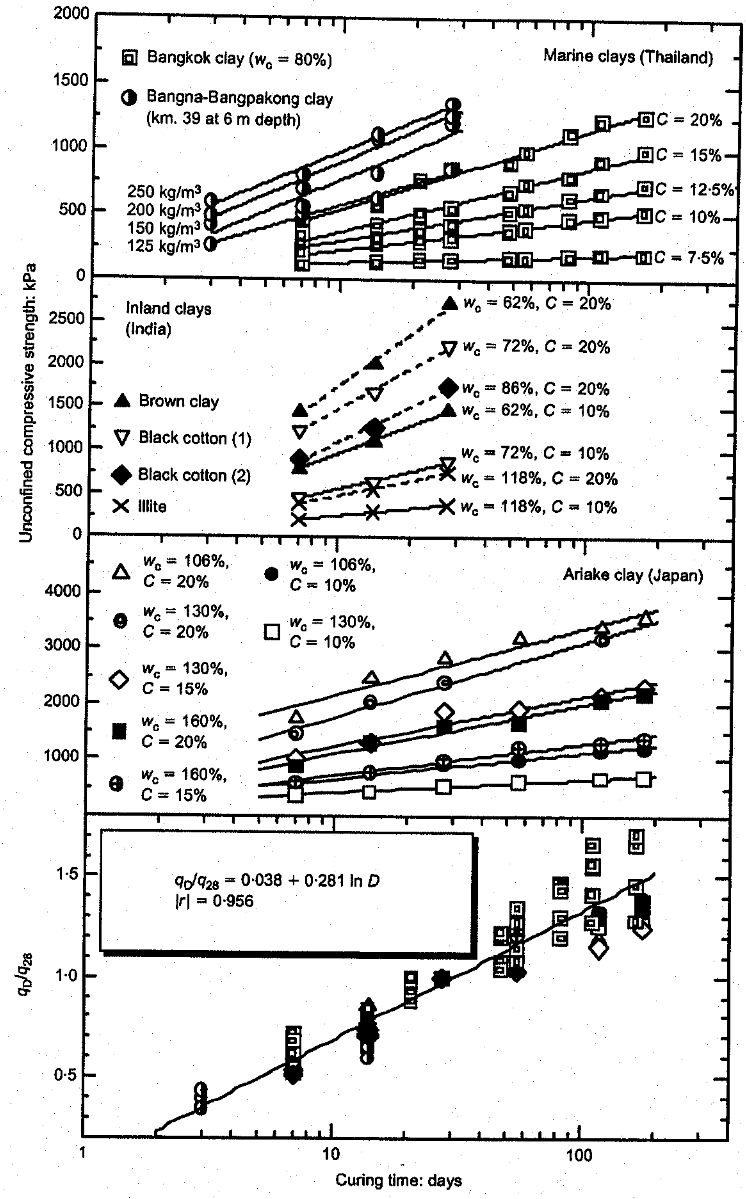

Fig. 9. Strength development with time and its generalisation at LI = 1·0–2·5

Table 1. Prediction of the cement-stabilised Bangna Bangpakong clay at 12 m depth (w_L = 86% and w_P = 34%, w_n = 92–107%) (Soralump, 1996)

Curing time: days	Cement: kg/m³	w_n: %	Density: t/m³	w_c: %	C: %	w_c/C	Strength, q_u: kPa	Predicted q_u: kPa
3	125	99·5	1·446	125·4	17·2	7·3	135	91
7	125	99·5	1·446	125·4	17·2	7·3	145	153
14	125	99·5	1·446	125·4	17·2	7·3	151	204
28	125	99·5	1·446	125·4	17·2	7·3	262	(data from)
3	150	99·5	1·446	130·5	20·7	6·3	155	112
7	150	99·5	1·446	130·5	20·7	6·3	180	188
14	150	99·5	1·446	130·5	20·7	6·3	185	251
28	150	99·5	1·446	130·5	20·7	6·3	282	314
3	200	99·5	1·446	140·9	27·6	5·1	161	145
7	200	99·5	1·446	140·9	27·6	5·1	207	244
14	200	99·5	1·446	140·9	27·6	5·1	218	325
28	200	99·5	1·446	140·9	27·6	5·1	345	406
3	250	99·5	1·446	151·2	34·5	4·4	170	169
7	250	99·5	1·446	151·2	34·5	4·4	227	285
14	250	99·5	1·446	151·2	34·5	4·4	298	380
28	250	99·5	1·446	151·2	34·5	4·4	436	475

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