EFFECT OF CLAY MINERALOGY ON COEFFICIENT OF CONSOLIDATION

RETNAMONY G. ROBINSON AND MEHTER M. ALLAM

Department of Civil Engineering, Indian Institute of Science, Bangalore-560 012, India

INTRODUCTION

The coefficient of consolidation (C_v) signifies the rate at which a saturated clay undergoes 1-dimensional consolidation when subjected to an increase in pressure. Measured in cm^2/s, C_v is a function of hydraulic conductivity, k (cm/s), coefficient of volume change, m_v (cm^2/kg), and unit weight of pore fluid, γ_w (kg/cm^3), and is expressed as:

$$C_v = \frac{k}{m_v \gamma_w} \qquad [1]$$

Terzaghi and Peck (1967) anticipated that, with decreasing void ratio (increasing consolidation pressure, p) both k and m_v decrease rapidly so that the ratio (k/m_v) and, hence, C_v, is fairly constant over a wide range of consolidation pressures. The variation of C_v with pressure has not received much attention in the past. Review of some available data in the literature on this aspect, however shows that C_v is not constant (Table 1) but varies with consolidation pressure. An examination of Table 1 shows that C_v increases with consolidation pressure for kaolinite but decreases with consolidation pressure for montmorillonite (bentonite). Both increasing and decreasing trends are observed (Table 1) for soils of unknown clay mineralogy. This inconsistency in the variation of C_v with consolidation pressure for different soils (clays in particular) needs reconciliation.

The C_v-p trends obtained in the laboratory for the clay minerals kaolinite, illite and montmorillonite and powdered quartz with water and CCl_4 as pore fluids are reported in this Note. These trends are evaluated relative to the mechanical and physicochemical factors which are known to influence the compressibility behavior of clays (Olson and Mesri 1970; Sridharan and Rao 1976).

EXPERIMENTAL

Three clay minerals (kaolinite, illite and montmorillonite) were used for the study. Ground quartz (<75 μm) prepared from Arkavathi River sand, was adopted as a material whose compressibility behavior is wholly governed by the elastic properties of the grains and by the surface friction characteristics. The physical prop-

erties of these minerals are reported in Table 2. Table 3 reports the exchangeable cations present in the clay minerals studied. While the cations for kaolinite and illite are essentially divalent (73% and 93%, respectively), the ratio of divalent to monovalent cations in the case of montmorillonite is practically unity.

Conventional 1-dimensional consolidation tests were performed on 60-mm diameter and 20-mm high soil specimens in the fixed-ring type consolidometer as per ASTM D 2435-80 (1989). The sides of the rings were smeared with silicone grease to reduce side friction. The samples of clay minerals were remolded at a water content of about 1.1 times the liquid limit. For the powdered quartz, a remolding water content of 37.6% was used. A load increment ratio (ratio of increase in pressure to the existing pressure) of 1.0 was adopted. The load was sustained sufficiently long to ensure completion of primary consolidation (48 h for montmorillonite in water and 24 h for all other tests). Falling head hydraulic conductivity tests were conducted prior to application of the next load increment.

Consolidation and hydraulic conductivity tests were also conducted on the powdered quartz as well as on the clay minerals with CCl_4 as the pore fluid. The nonpolar pore fluid CCl_4 was adopted to suppress the influence of exchangeable cations on the compressibility characteristics of the clay minerals (Olson and Mesri 1970). The minerals were mixed with CCl_4 to a slurry and were remolded in the consolidation ring. Values of C_v are derived from Equation [1].

RESULTS AND DISCUSSION

Figure 1 shows the variation of k, m_v and C_v with consolidation pressure for the 3 clay minerals with water as the pore fluid. Similar plots for powdered quartz are shown in Figure 2. As expected, k and m_v decrease with increase in consolidation pressure. The ratio of k to m_v (that is, C_v) is not constant over the pressure range of interest, contrary to the prediction of Terzaghi and Peck (1967). Further, the variation of C_v with the consolidation pressure is dependent on the clay mineral type. There is a decrease of C_v with pressure increase for montmorillonite and increases for kaolinite, illite and powdered quartz.

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Table 1. C_v-p variation in literature.

Source	Soil type	Liquid limit (%)	Plasticity Index (%)	Variation of C_v with pressure
Leonards and Ramiah (1959)	Residual clay	59.0	31.0	Decreases
	Glacial silty clay	28.0	8.0	Increases
Samarasinghe et al. (1982)	Sandy clay	27.0	14.0	Increases
	Don Valley clay	41.0	22.0	Increases
	New Liskeard clay	67.0	40.0	Increases
	Bentonite	118.0	72.0	Decreases
	Kaolinite	—	—	Increases
Nakase et al. (1984)	Kawasaki clay	53.6	26.9	Increases
Sridharan et al. (1994)	Kaolinite	49.0	11.8	Increases

It can be seen from Table 3 that over 50% of the exchangeable cations for the montmorillonite are Na, while Na is less than 1% of the exchangeable cations for the illite. To see whether the type of cation (valency) had any influence on the trend, experiments were conducted on predominantly homoionized clays. The 3 clay minerals were washed 5 times with 1 N sodium acetate solution to produce predominantly homoionized sodium clays. To produce calcium clays, the clay minerals were likewise washed with 2 N calcium chloride solution. The exchangeable cation concentrations in these treated clays are indicated in Table 4.

The C_v versus consolidation pressure trend for these homoionized clays in water are presented in Figure 3. Irrespective of the valency of the exchangeable cation, C_v increases with pressure for kaolinite and illite while it decreases for montmorillonite.

Figure 4 shows the coefficient of consolidation-pressure relationships of the minerals with CCl_4 as the pore fluid. For all the minerals, C_v increases with the consolidation pressure.

It may be noted that, on switching from water to CCl_4, the value of C_v is about the same for quartz, increases by 1 order of magnitude for kaolinite, increases by 4 orders of magnitude for illite and increases by 5 orders of magnitude for the montmorillonite. Substitution of the polar pore fluid (water) by CCl_4 (nonpolar fluid), which suppresses the diffuse double layer formation around the clay particles, resulted in about an average 30 (kaolinite), 4500 (illite) and 75,000 (montmorillonite) times increase in the hydrau-

lic conductivity. This is well understood to be due to the dispersed fabric associated with water being replaced by a structure of particle aggregations that possess larger effective pore sizes (Mesri and Olson 1971). Test results also showed that, in the pressure range used, m_v increased by about 30% of the original value for kaolinite and decreased by about 33% for illite and 20% for montmorillonite on changing the pore fluid to CCl_4. Powdered quartz exhibited only a 2.8 times increase in hydraulic conductivity and no significant change in m_v. Thus, the order of increase in C_v is practically related to the order of increase in the hydraulic conductivity.

It is thus seen that, in the case of montmorillonite, the trend of C_v-p relationship depends on the type of pore fluid used but, for illite, kaolinite and powdered quartz, it is independent of the pore fluid used. Useful parallels can be drawn from the past studies on the compressibility behavior of clay minerals.

Mechanisms Governing the Response of C_v to Change in Pressure

Powdered quartz is a mineral whose surfaces are practically devoid of exchangeable ions. The nature of the pore fluid (dipole moment, dielectric constant, concentration of dissolved ions, etc.) does not induce any long-range attractive and repulsive forces between particles, and gravity dominates over colloidal properties. The compressibility of the material is governed solely by the mechanical properties of the solid grains and by the lubricating effect of the pore fluid.

Table 2. Physical properties of the minerals used.

Property	Kaolinite	Illite	Montmorillonite	Powdered quartz
Liquid limit (%)	53	131	321	—
Plastic limit (%)	32	78	58	—
Plasticity Index (%)	21	53	263	—
Sand (%)	0	0	0	0
Silt (%)	71	36	2	98
Clay (%)	29	64	98	2

Table 3. Exchangeable cations present in the clay minerals studied.

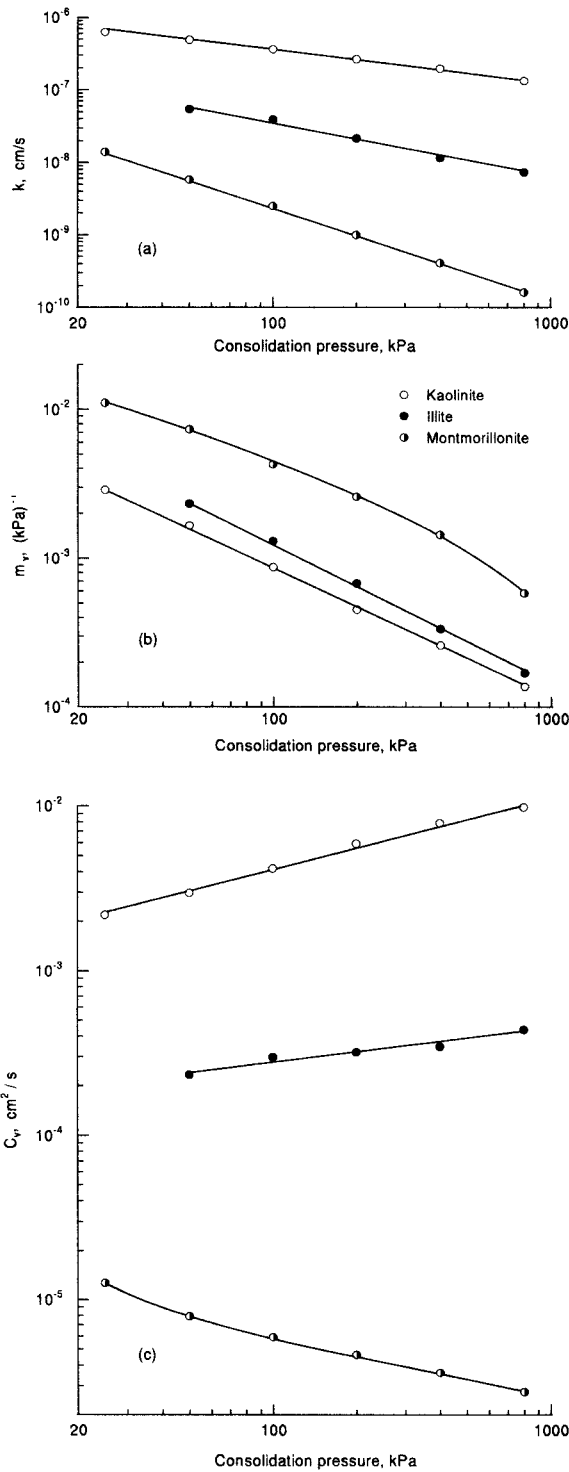| Cation	Cation concentration in meq/100 g		
	Kaolinite	Illite	Montmorillonite
Calcium (Ca)	1.5	18.7	38.5
Magnesium (Mg)	0.7	10.1	15.2
Sodium (Na)	0.5	0.3	58.4
Potassium (K)	0.3	1.8	0.7
Total	3.0	30.9	112.8

Figure 1. (a, b, c). Variation of k, m_v and C_v with consolidation pressure for the clay minerals with water as the pore fluid.
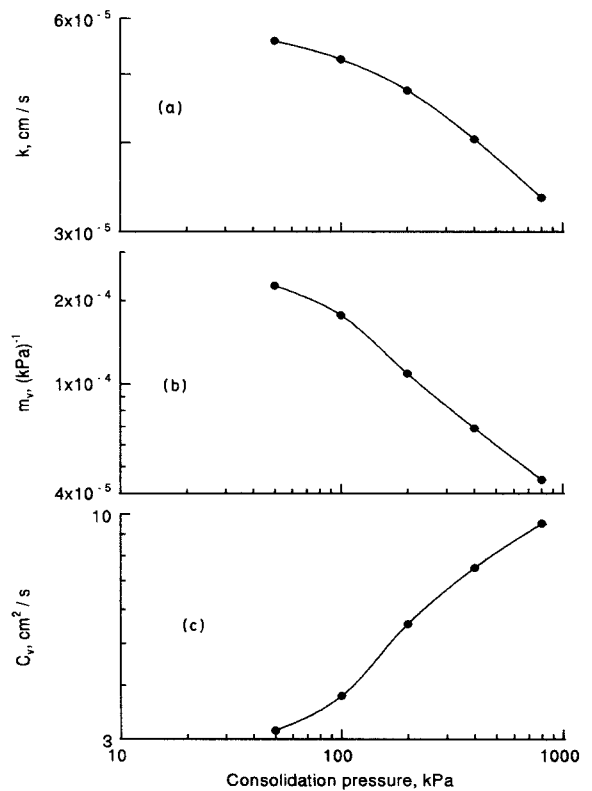

Figure 2. (a, b, c). Variation of k, m_v and C_v with consolidation pressure for the powdered quartz with water as the pore fluid.

On the other hand, the compressibility of clays is influenced by both mechanical and physicochemical effects (Olson and Mesri 1970), depending upon the type of mineral, saturating cation and the pore fluid. The term "mechanical" is used to denote short-range particle interactions controlled by the physical properties of the mineral particles, that is, by their strength and flexibility and by surface friction. The term "physicochemical" signifies comparatively long-range interactions between particles, especially through diffuse double layers. The virgin compressibility of kaolinite and illite, even in the case of polar pore fluids, is primarily controlled by mechanical effects, whereas

Table 4. Concentration of exchangeable cations in the homoionized clay minerals.

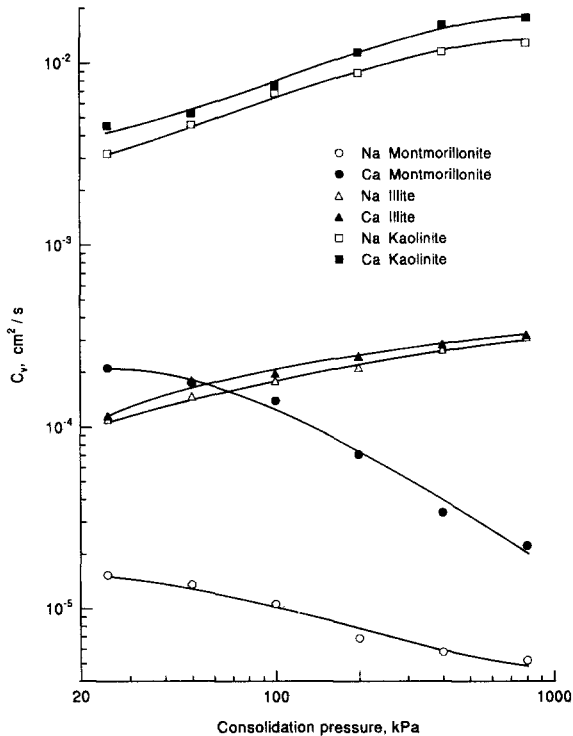| Clay type	Concentration of cations, meq/100 g			
	Ca	Mg	Na	K
Na-montmorillonite	14.65	7.82	85.7	0.60
Ca-montmorillonite	93.99	4.69	1.49	0.39
Na-illite	5.82	2.00	20.99	1.09
Ca-illite	23.25	2.73	0.75	1.13
Na-kaolinite	0.60	0.35	1.89	0.11
Ca-kaolinite	2.46	0.20	0.09	0.13

Figure 3.　Variation of C_v with consolidation pressure for the homoionized clay minerals with water as the pore fluid.

Figure 4.　Variation of C_v with consolidation pressure for quartz powder and the clay minerals with CCL_4 as the pore fluid.

physicochemical effects control the compressibility of montmorillonite (Olson and Mesri 1970). When non-polar pore fluids are used, the diffuse double layers around clay particles are suppressed and the compressibility of all clay minerals, including smectite, will be influenced mainly by mechanical effects (Olson and Mesri 1970; Sridharan and Rao 1976).

The C_v-p trends presented above show that, where the virgin consolidation is controlled by mechanical effects, as in the case of kaolinite, illite and powdered quartz in either water or CCl_4 as the pore fluid, the value of C_v increases with the consolidation pressure. For montmorillonite with water as the pore fluid (a situation wherein physicochemical effects control virgin consolidation behavior), it is seen that C_v decreases with pressure increase. With CCl_4 as the pore fluid (in which case diffuse double layer formation is suppressed), the virgin consolidation behavior is controlled by mechanical effects (Olson and Mesri 1970) and C_v increases with consolidation pressure. This suggests that, for clays, C_v increases or decreases with pressure, depending on whether the virgin compression behavior is controlled primarily by mechanical or physicochemical factors.

CONCLUSIONS

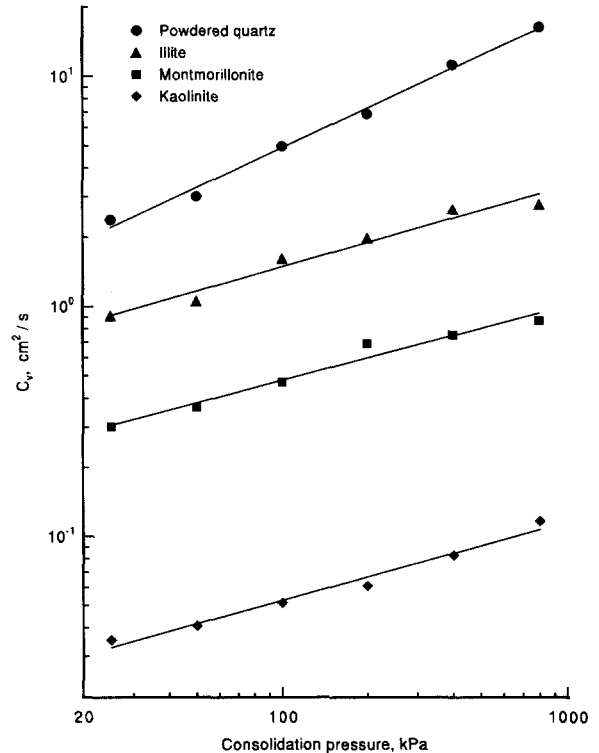The results of the study indicates that, in the case of clay minerals, the coefficient of consolidation is not

constant but varies with consolidation pressure. The apparently contradictory trends in variation of C_v with consolidation pressure seen in the literature can be reconciled on the basis of the virgin compression behavior. There is an increase of C_v with pressure for kaolinite, illite and powdered quartz, whose compressibility behavior is governed by mechanical factors. For montmorillonite with water as the pore fluid, the compression behavior is governed by physicochemical factors and C_v is found to decrease with increase in pressure. It is seen that, in clays, C_v increases or decreases with pressure increase, depending on whether the virgin consolidation behavior is controlled primarily by mechanical or physicochemical factors. Thus, the response of C_v to pressure increase in clays is governed by the mechanical and physicochemical factors that govern the compressibility.

ACKNOWLEDGMENTS

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