SOME STUDIES ON THE CRACKING OF SOIL-CEMENT IN JAPAN

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This paper mainly treats of the phenomenon of cracking in soil-cement under repeated loads, compared with the case of static loads, and the usefulness of the immediate opening of a soil-cement base to general traffic is emphasized from the good results of an in situ experiment. Concerning the cracking of soil-cement due to climatic action, the merits of a sandwich structure are pointed out. A method to reduce the shrinkage caused by the hydration of portland cement is reported based on an experiment using specimens in which ferrous oxide powder and calcium chloride are added to the soil-cement mixture.

•THE CAUSES of cracking in soil-cement involve, as is well known, (a) hydration of portland cement, (b) drying, (c) drop of temperature, and (d) effect of traffic loads. Among these causes, the author will consider here mostly the development of cracks in soil-cement under loads. On the other hand, the merits of the sandwich structure are pointed out with respect to the case when it is used for the soil-cement that can prevent cracking due to climate. The author will also report on the results of experiments he made to reduce the shrinkage caused by the hydration of portland cement by adding ferrous oxide powder to the mixture of soil and cement and utilizing the expanding effect of ferrous oxide fractions.

The behavior of soil-cement under loads was pursued both on specimens and model pavements under static and repeated loads. The investigation was particularly centered on a method allowing immediate opening to general traffic, based on the results of experiments carried out under repeated loads, and one of the results from an in situ experiment is introduced to verify the superiority of this work method.

PROPERTIES OF SOILS USED

The soils taken up as materials for soil-cement in this study are two kinds of gravelly sand (shortened form: A-soil), consisting of hornblend andesite and called "Shimabara-shodo", and a volcanic ash sandy soil (shortened form: B-soil) called "Shirasu." These kinds of sandy soils were used respectively for the pavements of Shimabara Turnpike (1961, 107,250 m^2) and Yamanami-Highway Turnpike (1964, 286,000 m^2).

The physical properties of these soils are given in Table 1.

TENSILE RESISTANCE OF SOIL-CEMENT UNDER STATIC LOADS

Tensile Strength of Soil-Cement Under Static Loads

The slab action of a soil-cement layer in increasing the effect of load diffusion may be evaluated by tensile strength or bending strength of specimens. The author (8) measured the value of unconfined compressive strength σ_c and bending strength σ_b using soil-cement specimens (4 by 4 by 16 cm) of the preceding two kinds of soils using the method for the cement-mortar strength test, with the results as shown in Figure 1.

It can be seen from Figure 1 that, in the case of the B-soil, both the values of σ_c and σ_b show considerable increases for a long time, compared with the case of the A-soil,

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and the value of σ_b/σ_c shows the larger value among the standard values generally known as $\frac{1}{4} \sim \frac{1}{5}$ or $\frac{1}{3} \sim \frac{1}{6}$.

Fiber Stress and Strain in the Soil-Cement Layer in a Model Pavement

The fiber stress and strain test (5) was carried out on a two-layered model pavement composed of soil-cement (B-soil plus 6 percent portland cement) placed in a concrete box 1.4 m square inside and 1.0 m deep. Figure 2 shows the result of measurement by using a strain gauge of the strain on the base of soil-cement aged 7 days under a circular load of 20 cm diameter and 6.0 kg/cm^2 load intensity. In this model pavement, the k_{75}-value (equivalent k-value to 75 cm diameter) on the layer beneath the soil-cement was 11.7 kg/cm^2.

As a result, soil-cement of 10, 15, and 20 cm thickness gave 80×10^{-6}, 120×10^{-6} and 50×10^{-6}, respectively. That these values are not exactly proportional to the thickness is considered to be due to the irregularity of curing of the soil-cement.

Now, if the modulus of elasticity of soil-cement is assumed as 2,000 kg/cm^2 and Poisson's ratio 0.2, fiber stress will become 0.20, 0.30, and 0.13 kg/cm^2 respectively. Although these stresses are quite small compared with those of Figure 2, they will cause hairline cracking by fatigue under repeated loads.

Cracking in Soil-Cement Cylindrical Specimens

The specimen was prepared by adding 5 percent portland cement to A-soil and was compacted by using a Harvard compaction apparatus (3.3-cm diameter, 7.2-cm length, and maximum diameter of soil particle 20 mm). The author (6) carried out two kinds of tests on the specimens: subjecting them to repeated loading every day, covering ages 1 day to 7 days, and the reverse case when loading is suspended. The results are shown in Figure 3. This figure shows the ratio of unconfined compressive strength to the strength of 7 days' cure, as the value of the ordinate.

Figure 3 leads us to the following conclusions concerning the effect of the condition of repeated loads on 7 days' strength of soil-cement:

1. According to the results, using only 1-day loading at ages between 1 day and 6 days, loading in the initial period of age, i.e., loading up to the second day, increased the 7-day strength, whereas loading on the third day to the fifth day decreased the strength more than the case of no loading. It seemed, however, that there was no deteriorating effect when loaded after 6 days.
2. According to the results of the experiment made on the case of continuous loading every day, beginning from a certain day during the 7 days' curing, the case of loading from the initial period of curing gives better results for 7 days' strength, while the result was worse when loading was started from the second to the fifth day of age. Such a phenomenon is affected by the load intensity, where the larger the load intensity is, the more the age giving maximum effect shifts toward larger age in most cases. On the other hand, in the case when the load intensity is small, the effect on strength is small.
3. According to the results from continuous loading, started from the first day of age, the effect varied with the magnitude of the load, but when loading was stopped around the third to the fourth day, the 7-day strength was maximum. This result is considered to be the reverse phenomenon of the result of conclusion 2 above.

Effect of Repeated Loads on Soil-Cement Layer

The author intended to detect how hairline cracking developed in a soil-cement layer (B-soil plus 4 percent portland cement), showing the tendency to retrograde into the state of crushed stone mass.

In this experiment (11), a circular load of 20 cm diameter and 6.37 kg/cm^2 load intensity is imposed on the surface of a soil-cement layer in such a model pavement as mentioned before, after it has been subjected to 7 days' cure, in a cycle of 2-second loading and 4-second unloading.

Table 1. Properties of the soils for soil-cement.

Designation	Specific Gravity of Particle	Grading at Borrow Pit (percent)		Classification	JIS Compaction Test	
		<0.074 mm	<0.95 mm		Optimum Moisture Content (percent)	Maximum Dry Density (g/cm³)
A-soil	2.72	2 ~ 3	5 ~ 6	A-1-a	13.6	1.946
B-soil	2.69	7 ~ 8	62 ~ 65	A-3	21.0	1.625

Figure 1. Relation of age to the compressive and tensile strengths of compacted samples.

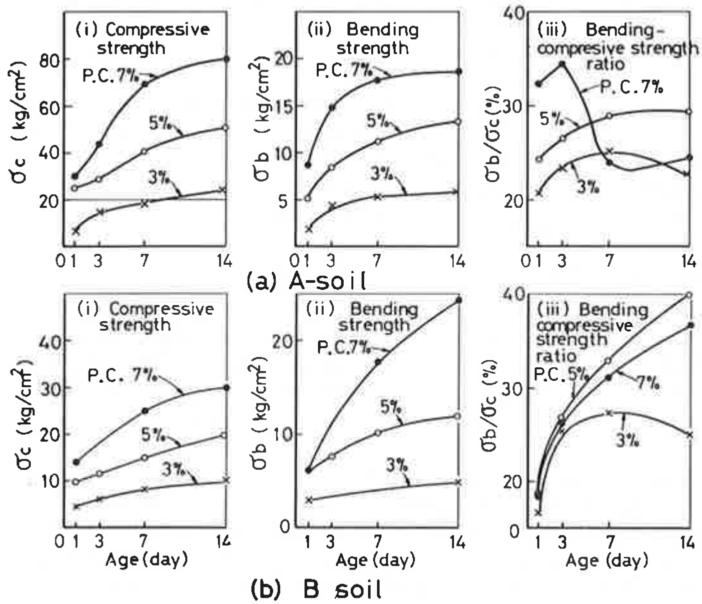


Figure 2. Compressive and tensile strains in soil-cement under the static load for pavement design.

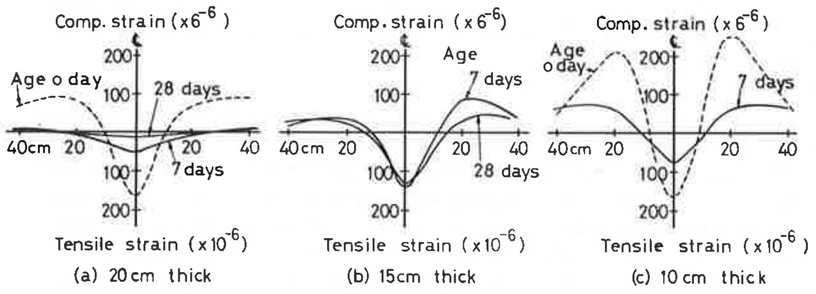
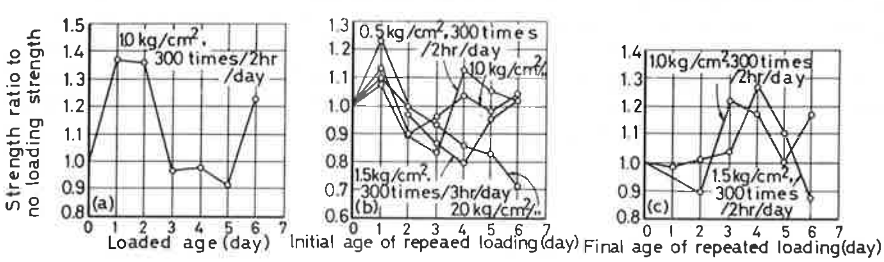


Figure 3. Effect of repeated loads on the 7 days' unconfined compressive strength of soil-cement samples.



In order to measure the modulus of elasticity and the total sum of opening of hairline cracking at the moment of loading, there were buried a meter for modulus of elasticity and a crack-meter, as shown in Figure 4, in the soil-cement layer. The surface settlement at the moment of loading was also measured by using a dial gauge. These measured values are given in Figure 5 along with the frequency of repeated loading.

The results of this experiment revealed that hairline cracking develops in the soil-cement layer owing to repeated loading, causing bending resistance to decrease, and consequently the modulus of elasticity decreases while deflection increases. In this process, it is pointed out that the modulus of elasticity decreases almost in logarithmic fashion against the cycle number of repeated loading, as shown by the following equation:

$$E_N/E_0 = a + b \log_{10} N$$

where E_0, E_N = modulus of elasticities at the initial and repeated cycle and N, a, b = constants determined by the bearing capacity of the layer beneath the soil-cement layer. The less the value of b, the larger the bearing capacity of the lower layer is.

This relation suggests the possibility of accounting for the effect of traffic volume numerically in designing the pavement containing a soil-cement layer.

Experiment on the Immediate Opening of Soil-Cement Base to General Traffic

Building of the Experimental Road—An in situ experiment was made during the period from October 1959 to January 1960, prior to deciding on the justification of adopting the method of immediate opening of the soil-cement base to general traffic, in the reconstruction of Shimabara Road into an asphalt concrete pavement for a turnpike where it was formerly a gravel road.

The location chosen for the in situ experiment was on the route planned for the major work and where the quality of the subgrade was comparatively inferior. The location was on a longitudinal grade of 2.5 percent, where the traffic volume was approximately 400 vehicles. In this experiment, as given in Table 2, soil-cement layers 6 m wide and 20 m in length each were laid in 6 different sections. In each, earth pressure cells were installed on the top of the subbase or the bottom of the soil-cement layer. The diameter of the pressure surface was 60 mm and the capacity of the cells was 7 kg/cm^2. Mixing of soil-cement was carried out by stationary plant and the macadam roller. Placing work was done on half the width of road at a time, so that the normal traffic was not interrupted. The measured values of the field densities by the sand-cone method on the day of placing are given in Table 3. Comparing these with the optimum condition of compaction by the CBR test (55 blows per layer), the result showed a very high degree of compaction, as seen in Table 4.

Bearing Function of the Soil-Cement Layer—For a surface settlement, due to the plate loading test, of 0.5 mm, a relation such as that shown in Figure 6(a) was obtained for the variation in the ratio of vertical stress σ_z on the bottom surface of the soil-cement, as indicated by the earth pressure cells divided by the load intensity p on the surface. Up to the age when the value of σ_z/p becomes less than the value calculated from the equations of Boussinesq or Westergaard, the soil-cement can be said to have maintained its property as a soil mass. After this time the layer of soil-cement rapidly increases its load-diffusion capacity, reaching its final magnitude at 7 days. This half-way age corresponds to the transitional age shown in Figure 5, which is plainly seen to be an important period from the viewpoint of load-diffusion capacity. However, because the pressure distribution due to actual measurement of sand is usually different from the theoretical one, the above age is by no means accurate.

Assuming that the vertical stress σ_z in the base of soil-cement is uniformly distributed by a certain angle of load diffusion, the value will be calculated from the value of σ_z/p. The values of angle of load diffusion with age are as shown in Figure 6(b). No difference is observed between the section with immediate traffic release and that with ordinary 7 days' curing due to the effect of such a load diffusion.

Figure 4. Installation of crack-meter and elastic modulus-meter in the soil-cement layer.

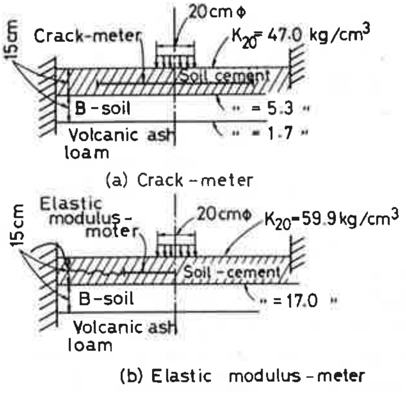


Table 2. Soil-cement layers used for in situ experiments.

Section No.	Cement Content (percent)	Actual Depth of Soil-Cement on Pressure Meter (cm)	Method of Opening to Traffic
1	5	13.5	Opened after seal-coating as well as after compaction
2	5	12.1	
3	4	14.5	
4	5	10.6	Opened after ordinary 7 days' curing
5	5	13.1	
6	4	15.2	

Note: Test section contained the following layers: top layer, soil-cement (maximum diameter 30 mm); middle layer, selected material (Shimabara-shodo, maximum diameter 50 mm); bottom layer, subgrade (organic-volcanic ash loam).

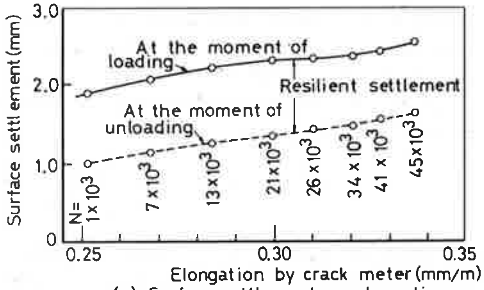
Table 3. Density and moisture content on soil-cement layer.

		Dry Density			Moisture Content		
Section No.	Cement Content (percent)	Average (g/cm³)	Standard Deviation (g/cm³)	Coefficient of Variation (percent)	Average (percent)	Standard Deviation (percent)	Coefficient of Variation (percent)
1	5	2.128	0.094	4	7.1	0.58	8
2	5	2.140	0.088	4	8.2	0.36	4
3	4	2.175	0.051	2	7.5	0.44	6
4	5	2.187	0.047	2	7.8	0.36	5
5	5	2.145	0.062	3	7.7	0.18	1
6	4	2.177	0.125	6	8.5	0.22	3

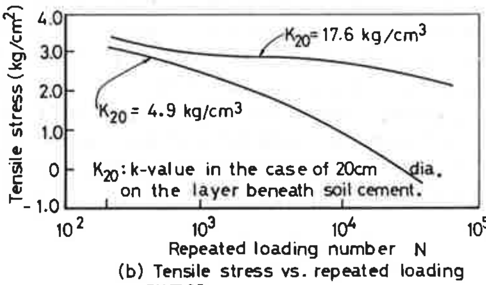
Table 4. Compaction tests on soil-cement layer.

	CBR Compaction Test (55 blows per layer)		In Situ Test	
Cement Content (percent)	Optimum Moisture Content (percent)	Maximum Dry Density (g/cm³)	Moisture Content (percent)	Dry Density (g/cm³)
4	9.7	2.085	8.0	2.176
5	9.4	2.092	7.7	2.154

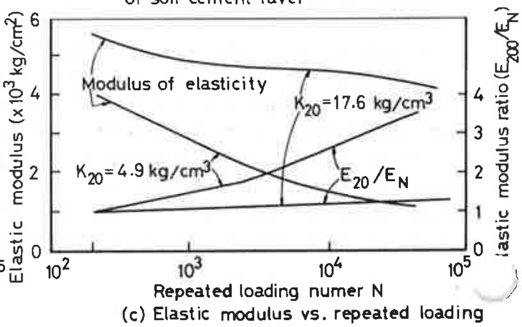
Figure 5. Behavior of soil-cement layer under repeated loads.



(a) Surface settlement vs. elongation of soil cement layer



(b) Tensile stress vs. repeated loading numer



(c) Elastic modulus vs. repeated loading number

When the ratio of modulus of elasticity was calculated by means of Burmister's theory, using the modulus of elasticity measured by the plate-bearing test under an assumption that the part below the subbase acted as bottom layer and that there was 0.5-mm surface settlement of soil-cement, the result was as shown in Figure 6(c), where the transitional age is, strictly speaking, somewhat altered to the left compared with the case of Figure 6(b). However, both figures are generally similar. From this result no real difference was found between the section with immediate opening to general traffic and the section with 7 days' curing.

Cracking in the Soil-Cement Layer—When the unconfined compressive strengths of core samples cut from the soil-cement layer older than 7 days were examined, as shown in Figure 7, the strength of samples was vastly different from the results obtained so far in this paper. They show an increase in strength up to 28 days' age. However, no real difference is found between the section using immediate traffic release and that with ordinary curing. Taking an average, the section with immediate opening to general traffic seems to show a little higher strength.

Figure 8 shows the general condition of surface cracking after about 70 days. The cracks were judged invariably to be hairline cracks, and it is remarkable that they were found in the section with ordinary 7 days' curing but not in the section with immediate opening to general traffic. In part of No. 6, those cracks found near the edge are considered to be due to inadequate lateral support.

MERIT OF SANDWICH STRUCTURE USED FOR SOIL-CEMENT

The sandwich structure of soil-cement introduced here refers to a form of pavement that is not only used for the base course but also is placed on subgrades of low bearing capacity in poor soil-cement mixture; the author has described it elsewhere (9, 10, 12). The utilization of the sandwich method was approved by the Japan Road Association (3). While the effect of this method is reasonably manifest in the case of repeated loading, the field test made on it and also the experiment concerning low bank roads (2) have revealed some properties: (a) deflection decreases on the surface of the subgrade, (b) there is a tendency toward stress distribution, and (c) the density of the soil on the lower soil-cement at the time of placing increases.

Since the lower soil-cement layer in this structure suffers no detrimental effect from climate, as pointed out by Schnitter and Bollier (4), who studied the use of soil-cement on subgrades, it is durable against cracking for a long time. Such a form has been actually adopted at Schiphole Airport in the Netherlands (1).

The author (13) reported on his idea to build a multiple-sandwich-structure bank by using soil-cement and plain soil layers when the soil is extremely erosive in order to prevent gully erosion. In this case, the soil-cement layers in the bank are safe against cracking almost permanently.

However, such an effect on the lower soil-cement layer has not been directly observed yet.

AN ATTEMPT TO REDUCE SHRINKAGE DUE TO HYDRATION OF PORTLAND CEMENT

Because shrinkage of soil-cement due to the hydration of portland cement increases as the amount of portland cement added is increased, this hinders soil-cement from displaying its characteristic slab action sufficiently.

With a view to reducing such shrinkage, the author (7) carried out an experiment by adding ferrous oxide powder (which is obtained at low cost as a refuse from iron factories) and calcium chloride to the mixture of soil and portland cement at the time of mixing and letting the former ingredient expand. In this method, ferrous oxide powder (shortened as Fe) is supposed not to hinder portland cement from hydrative hardening.

This experiment was made on a rectangular specimen (4 by 4 by 16 cm) using B-soil. After curing it under conditions of 23 C temperature and 90 percent humidity, measurement was carried out, with the amount of shrinkage expressed as linear-shrinkage percentage, and bending and compressive strengths were both evaluated.

Figure 6. Relation of age to the function of the soil-cement base.

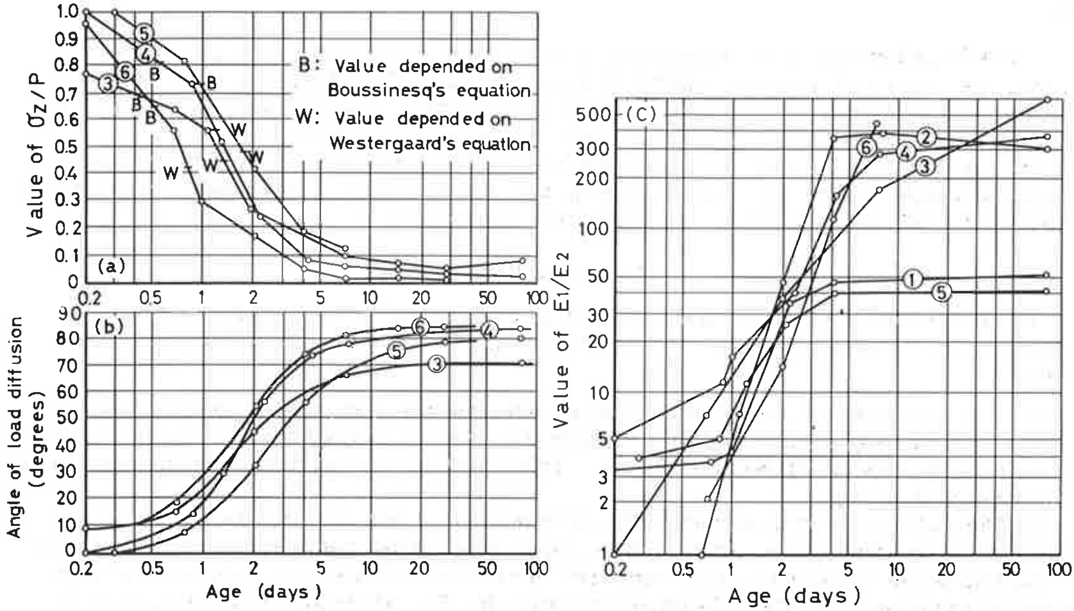


Figure 7. Unconfined compressive strength of cut-core samples from the soil-cement base.

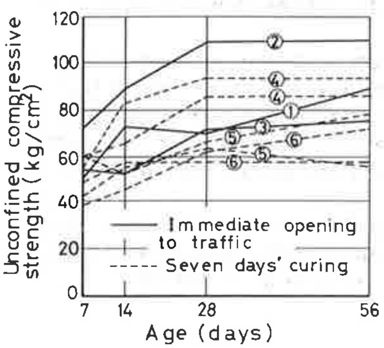


Figure 8. Surface cracks in the soil-cement layer at about 70 days' age.

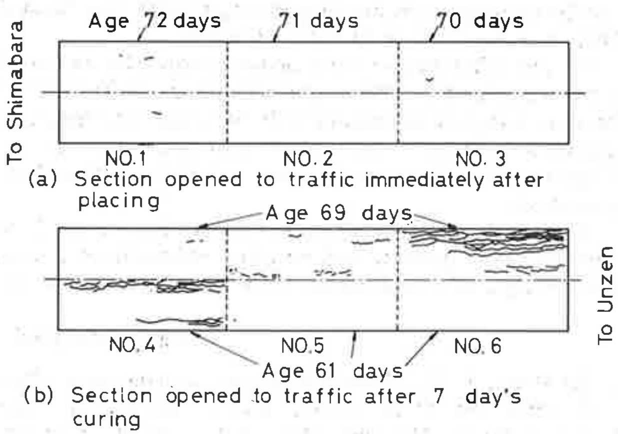
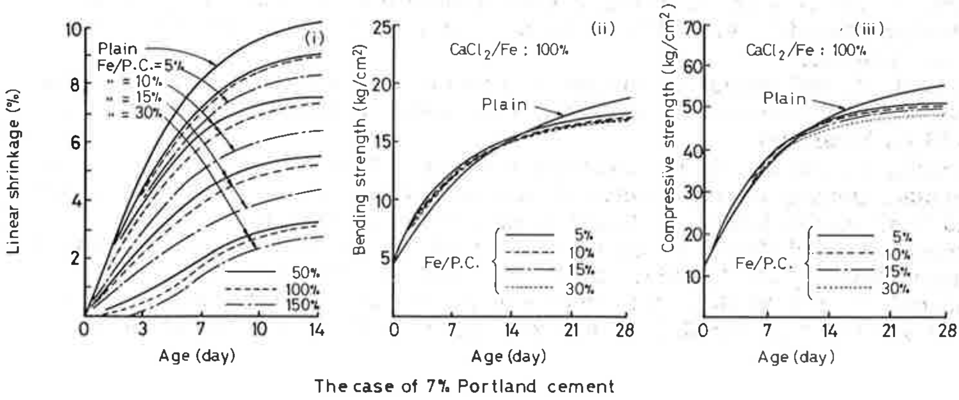


Figure 9. Effect of ferrous oxide-calcium chloride on the mixture of soil-cement.



It has been learned from the results of these tests, as shown in Figure 9, that the larger the amount of Fe-$CaCl_2$ added, the less the rate of shrinkage became, and that bending and compressive strengths scarcely decreased. The effect of the mixing ratio of Fe/$CaCl_2$ was, however, small within the range of 50 ~ 150 percent.

Soil-cement of such a small shrinkage as this may probably be applied not only to the soil-cement that is used by compacting but also to plastic soil-cement, soil-cement slurry, and soil-cement grout. However, no field test on this was made.

CONCLUSIONS

The conclusions drawn from the results of a series of experiments made on specimens, on model pavements, and in situ with respect to cracking of soil-cement are as follows:

1. The decrease of slab action of the soil-cement for pavement is approximately linear when the logarithm of repeated loading number is plotted against the development of hairline cracks under repeated loads. This relation may be introduced quantitatively into pavement design.
2. There is an interim period in the development of soil-cement during which it is susceptible to unfavorable effects from stress; this occurs between the early age when it maintains the properties of granular soil mass and the age when hardening has progressed far enough to attain its ultimate strength. It is therefore most desirable to open it immediately to general traffic at the early stage of its age and then suspend the traffic as long as the interim period lasts. As a matter of practice, however, this method is too complicated to follow, so, if we are to choose one of the two cases, to open immediately to general traffic or to follow the former method and open the pavement after 7 days' curing, as far as cracking is concerned, the former method is better. The immediate opening of general traffic has been distinctly better than the case of 7 days' curing at an in situ experiment.
3. The efficiency of the bearing capacity of the pavement in which soil-cement is used in a sandwich structure has been confirmed in the field, and it is proposed that the durability of pavement will be improved more by the advantage it offers; that is, it causes no cracks in the lower soil-cement layer. As to such a non-cracking property of the lower soil-cement layer, however, the author has not yet performed direct observation.
4. An attempt to reduce shrinkage due to the hydration of portland cement by adding ferrous oxide powder and calcium chloride to a soil-cement mixture had little effect on the strength of a specimen, although this attempt is yet to be tested in the field.

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