Resilient Properties and Microstructure of Modified Fly Ash–Stabilized Fine-Grained Soils

DAVE TA-TEH CHANG

A comprehensive study on the application of Class F fly ash for stabilizing subgrade soils in Taiwan is presented. Lime (or cement) was used with fly ash to enhance its self-cementing behavior in the study. Laboratory testing included using the plasticity index method to determine the optimum percentages of additive and fly ash. Through a resilient modulus (MR) test program, these percentages were confirmed. A section of test road with treated subgrade constructed on the West Coast Highway has been open to traffic for 40 months to date. A field investigation of this section was part of this study. Results from field California bearing ratio tests indicate that treatment of the subgrade soil had improved its properties by a factor of 10 to 15. Specimens obtained from the field were also evaluated through an MR test program, and the results were compatible with those for laboratory-made samples. Finally, a microstructure study is presented showing significant cementitious materials in laboratory and field specimens. Confidence about the future application of Class F fly ash for stabilizing subgrade soils in Taiwan and for handling this problematic waste material is provided.

Fly ash is causing serious disposal problems in Taiwan, where it occurs only in the Class F form as a by-product of electricity generation in thermal power plants. Recently, the use of fly ash as a stabilizer for subgrade soils has been the subject of much research. The project, sponsored by the Taiwan Electric Power Company and the Taiwan Highway Bureau, is recognized as the most complete study on this subject.

Hydrated lime was intentionally used as a modifier to enhance the self-cementing behavior of Class F fly ash; the modified fly ash (FA′) yielded from this treatment process has been found (*1*) to exhibit behavior similar to Class C fly ash, which is a well-known stabilizer for problem soils. The preliminary study of this project evaluated the significance of improvements in terms of strength and durability. These were viewed as the best basis for determining the optimum F/L (fly ash/lime) ratios, as well as the optimum amount of FA′ for use with fine-grained soils. The main program, which is presented in this paper, included an evaluation of the resilient modulus MR behavior for treated soils. The pavement-thickness design and layout of the test road were performed before the roadway was constructed, which at the time had been open to traffic for 40 months. The roadway subgrade was tested for its California bearing ratio (CBR) properties and sampled for further laboratory tests. Laboratory and field samples were tested for pH and MR and the microstructure of the FA′ treated soils.

Civil Engineering Department, Chung Yuan University, Chung Li, Taiwan 32023, R.O.C.

BACKGROUND AND PRELIMINARY STUDY PROGRAM

Modification of the physicochemical properties of fine-grained soils with Class C fly ash results in improved strength and durability. Much has been reported about how Class C fly ash affects soil properties, but there has been little investigation in Taiwan into the effects of using Class F fly ash. Class F fly ash, which has low CaO content (<10 percent) and thus exhibits little or no self-cementing potential, has generally been considered waste in Taiwan, leading to pollution problems. In the study by Chang and Yu (*1*) on the use of Class F fly ash as subgrade-soil stabilization, FA′ (Class F fly ash containing hydrated lime as an additive to enhance self-cementing behavior) was found to readily improve strength and reduce shrinkage-swelling potential. Following the pH method of Eades and Grim (*2*), Sabry and Parcher (*3*) succeeded in defining the Fly Ash Modification Optimum (FAMO) by using a similar pH measurement plot. This method was adopted as a means to select FA′ percentages for improving engineering properties. The report (*3*) did not include recommendations for optimum ratios of F/L, because only two (8:1 and 12:1) were studied. The typical guideline for using fly ash, provided by the U.S. Department of Transportation and FHWA, requires improvement in strength and durability. Because fly ash is obtained at no cost in Taiwan, the limitation of strength of at least 400 psi may not be necessary. Thus, an applicability study based on the potential improvements in strength and durability was the first goal to be achieved with respect to using fly ash in Taiwan.

The preliminary program included index testing to evaluate the materials used and to determine the parameters for preparing compacted specimens. Next, specimens were prepared, using the Harvard Miniature Compaction Device, for the unconfined compression test. The specimens were then sealed with polyvinyl chloride (PVC) film to prevent moisture from escaping during the curing period. The lateritic soil (Soil L) and weathered mudstone (Soil M) used in this part of the study were obtained from the northwestern and the southwestern areas of Taiwan, respectively.

F/L ratios of 1, 2, 4, 6, 8, 10, and 12 were adopted for FA′. As determined by pH test analyses, results of FAMO for FA′s used in these soils are tabulated in Table 1. The quantity of FA′ used for stabilization was preliminarily studied by using 0.5, 0.8, 1.0, 1.5, 2.0, 2.5, and 3.0 times their respective FAMO's (percent) to the soil by dry weight. This resulted in the use of a method based on unconfined compressive strength for the following test program: specimens using FA′ with the amount of 1.5 × FAMO and 2.0 × FAMO. For evaluating the improvement in terms of strength and durability behavior, 728 specimens were prepared and tested for

TABLE 1 Values of FAMO for FA′ to Soil L and Soil M (*2*)

Soil Type	F/L		1		2		4		6		8		10		12	
Soil L	FAMO FA'/soil,%		10		12		15		17		18		19		20	
	FA	L	5	5	8	4	12	3	14.6	2.4	16	2	17.3	1.7	18.5	1.5
Soil M	FAMO FA'/soil,%		5		6		8		9		10		11		12	
	FA	L	2.5	2.5	4	2	6.4	1.6	9.7	1.3	8.9	1.1	10	1	11.1	0.9

the proposed program (*1*). During the series of wet-dry tests, 1- and 12-cycle saturation treatments (*4*) were performed. For evaluation and comparison purposes, the ratio of strength of treated to strength of untreated specimens was determined and plotted against various percentages of lime compared with the sum of FA plus soil by weight [L/(FA + S)] for all treatments. The representation of L/(FA + S) was determined in the belief that for each treatment condition, a certain amount of lime would have a combined influence on the fly ash used (F/L) and the soil as FA′. Findings indicate that the optimum value of L/(FA + S) for lateritic soil and weathered mudstone are 3.5 and 2.0 percent, respectively. Because calcium (as a factor of F/L) plays an important role in the chemical reactions between FA and soil, the property of the clay particles reflected by plasticity may be a basis for quick determination of an optimum value for L/(FA + S). Therefore, for other fine-grained soils, values of L/(FA + S) may be interpreted by PI, ranging from 12 to 34, with L/(FA + S) values of 2.0 and 3.5 percent, respectively. The ratios 4, 6, and 8 for F/L are recommended for other soils and could be used to determine the FAMO by the pH method. Knowing the L/(FA + S) in addition to the F/L and FAMO, the combination could be adapted as desired (Table 2). It is necessary to reiterate the limitations applicable when determining the desired combination:

- F/L ratios: 4, 6, 8.
- Amount of FA′: 1.5 and 2.5 times the FAMO.
- Acceptable L/(FA + S) values: should be close to but definitely no less than, the interpreted value by PI.

The following equation has been derived for obtaining the value of L/(FA + S) for other soils of these types:

$$\text{L/(FA + S)} = \frac{3.5 - 2.0}{34 - 12}(\text{PI} - 12) + 2.0$$

$$= 0.07\text{PI} + 1.16 \qquad (1)$$

TABLE 2 Selection of F/L and Times of FAMO Based on Optimum Values of L/(FA + S)

Soil L (L/(FA+S)=3.5%)		Soil M (L/(FA+S)=3.5%)	
F/L	FA'/soil, %	F/L	FA'/soil, %
6	1.5×FAMO (17 %) FA=14.6 , L=2.4	4	1.5×FAMO (8 %) FA=6.4 , L=1.6
8	1.5×FAMO (18 %) FA=16 , L=2	6	1.5×FAMO (9 %) FA=7.7 , L=1.3

Because the previous findings were to be directly used in the pavement thickness design for the test road, an MR testing program was subsequently completed at the Highway Bureau's request.

RESILIENT MODULUS PROGRAM

Because the FA′ stabilized subgrade soil was to be applied to pavement thickness design, the next step was to verify the suitability of the strength-based formula by investigating MR characteristics. Of the two test roads (denoted A and B) provided by the Highway Bureau, the subgrade of Test Road A was classified as a CL soil, and it was included in the program. Research by Chang and Chang (*5*) indicates that portland cement provides the same results as lime when used as an additive for Class F fly ash and is relatively inexpensive. It was therefore incorporated for this section of the program. To facilitate differentiation, FA′ containing lime is denoted as FA′*l* and those containing cement as FA′*c*.

Modified MR Testing Device

The need to obtain reliable MR data for treated subgrade soil in the proposed program prompted the modification of the existing standard testing device. To control the testing and data-acquisition process, a computer program for determining MR of a fly ash-treated subgrade soil—MRSS II—was developed and revised from MRSS (*6*) (a program developed to control MR testing of subgrade soil) using an A/D convertor for data processing. The software was capable of simulating various testing conditions, such as load duration, cycle duration, and varying repeated loads. For monitoring purposes, the software was written to plot the stress time and deformation curves, which were found to resemble the shape of a haversine curve, as shown in Figure 1. Through the dynamic calibration procedure (*7*), the performance of this modified testing device was found to be reliable, accurate, and ready for the testing program.

Materials and Experimental Program

In this study, which focused on fine-grained soils, the selected samples of the lateritic soil (Soil L) and weathered mudstone (Soil M) were the same as in the preliminary program. In addition, soil from the road subgrade of the test road was studied. This test road is located in Kaohsiung County on the Mituo section of the Highway Bureau's West Coast Highway project between kilometer marks 217 + 100 and 218 + 100, and is designated section A, and the soil

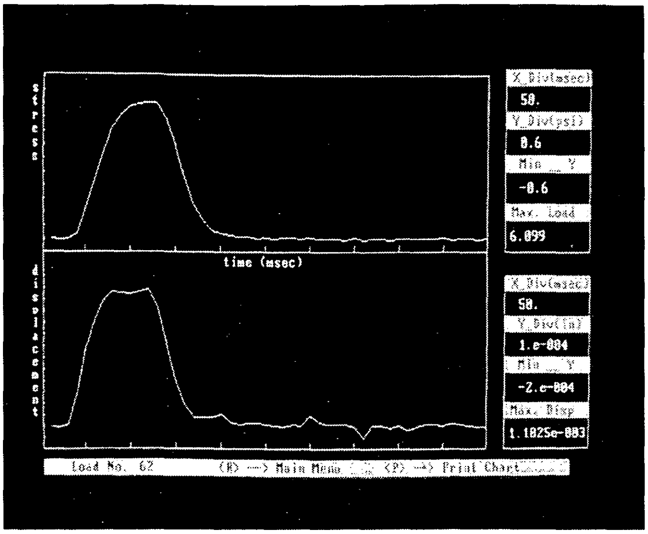

FIGURE 1 Typical stress-strain curve monitored by MRSS II software.

is designated as Soil A. The liquid limit of Soil A was 38 percent, and its plasticity index was 21 percent. So by the unified system, Soil A was classified as CL. Using the selected F/L ratios or fly ash/cement (F/C) ratios of 2, 4, 6, 8, and 10, pH tests were conducted. In terms of the FAMO values for these soils, there were only slight differences between FA′ containing a lime additive and those containing a cement additive. To facilitate analysis and comparison, the two were treated as providing the same values, as shown in Table 3. In accordance with the results explained above, the amount of FA′ used was 1.5 × FAMO and 2.0 × FAMO.

MR tests were conducted in accordance with the procedures delineated in AASHTO T274–82 (*8*). Considering the stress behavior of higher tire pressures, the deviator stress was set at 82.8 kPa (12.0 psi) instead of 6.9 kPa (1.0 psi). Conditions of optimum moisture content (OMC) and maximum dry unit weight were adopted for preparing MR specimens. Specimens were molded by static compaction, sealed with PVC film and wax, and then cured in a moisture room for 7 days. The requirements for rapid curing (*9*) were adopted; therefore, the temperature was set at 38°C (100°F).

The MR testing procedures were conducted under two sets of conditions: the OMC state and a saturated state. Each cured specimen was placed in a triaxial cell for MR testing at the OMC state. After this test was complete, back-pressure saturation was conducted for 24 hr to achieve the normal saturation requirement of 95 percent before carrying out the MR testing procedures. Reduction of back pressure (complete depressurization) had to be conducted in several stages with 30-min static intervals between each stage to avoid the adverse influence of excessive pore water pressure on MR behavior.

Results Analysis and Evaluation

Performance Differences from Fly Ash Additives

Because unconfined compressive strength had previously been adopted as a convenient index, MR properties were used in this study as an additional comparison and to verify the mutual conformity of the two. To ensure that the readings were conservative, MR values (*10*) corresponding to σ_d = 41.4 kPa (6.0 psi) and the MR values corresponding to the stress transfer values of high tire pressures, σ_d = 82.8 kPa (12.0 psi) were also taken into consideration. These values are compared in Figure 2. In each case, the MR values corresponding to σ_d at 41.4 and 82.8 kPa are provided. To gain an understanding of the development potentials for these MR values and to simplify the results for analysis, all curves were drawn through points midway between the saturated and the unsaturated (OMC) values. Comparing the effect of saturation on MR values in Figure 2, it is apparent that its influence is not significant. In some cases the structure of the grains actually became more stable as sufficient water was provided for hydration purposes—a factor, which in durability terms, is positive indicator for stable applications of fly ash. Considering the situation for the influence of lime and cement additives, in only one case (Soil L) does the influence of lime slightly exceed that of cement. Lime is the preferred additive in this case because the relatively high PI of Linkou Lateritic Soil (Soil L; PI = 34) means that there is a fairly high demand for CA^+ during the initial phase of the cation exchange reaction. In those soils with lower PI values (the PIs for Soil M and Soil A are 12 and 21, respectively), the ions required for the cation exchange reaction can be obtained in sufficient amounts from cement. Most of the soil-grain cementing agents are derived from the hydrating effect of the cement because these achieve earlier stability than the pozzolan effect of lime. This analysis is in complete correspondence with the chemical mechanisms of soil stabilization; therefore, the observed properties are credible.

Considering that local cement is cheaper than lime and that highly plastic soils are rarely encountered in Taiwan, it can be recommended that for practical applications for these soils cement would be the additive of choice.

Review of PI-Interpretation Method

Generally speaking the improved MR properties in Figure 2 allow one to combine the best parameters [L (or C)/FA + S] and ascertain

TABLE 3 Values of FAMO for FA′ to Soil A

F/L or F/C		2		4		6		8		10	
FAMO FA′/soil, %		8		11		13		14		15	
FA	L or C	5.3	2.7	8.8	2.2	11.1	1.9	12.4	1.6	13.6	1.4

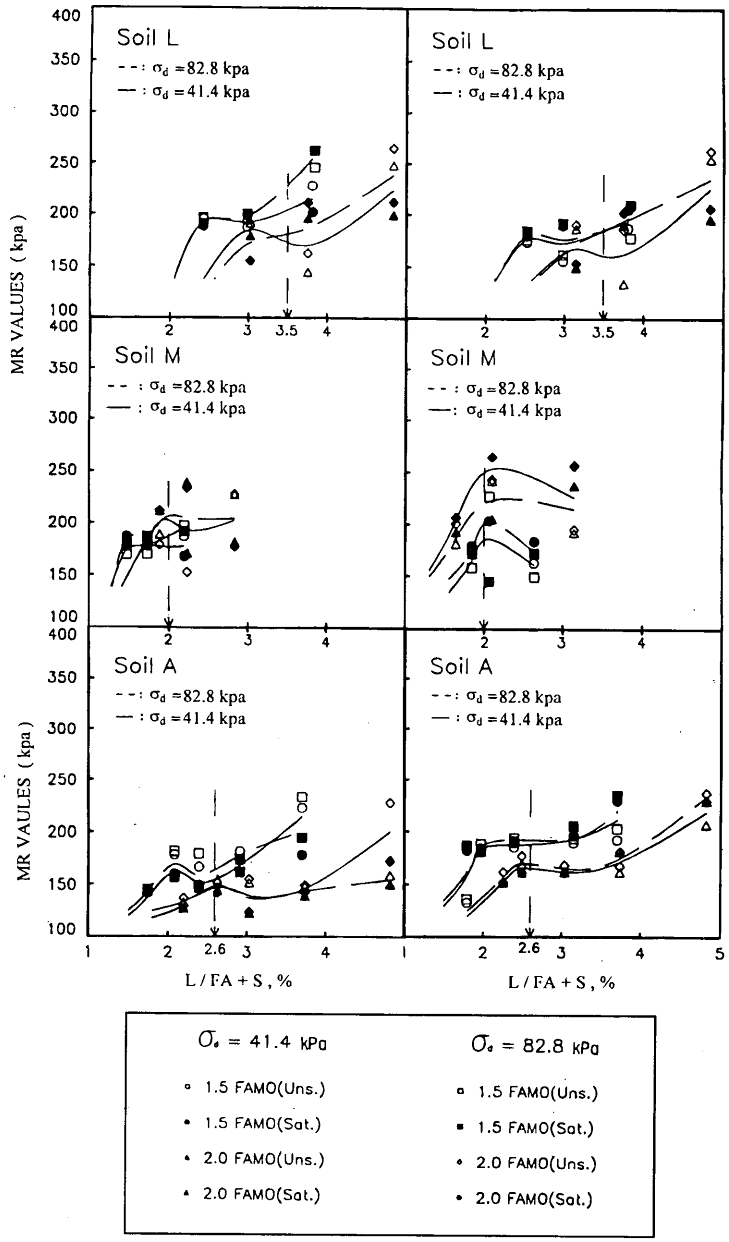

FIGURE 2 Relationship of C (or L)/FA + S to the development of MR values.

rational and conservative values based on 1.5 and 2.0 times their FAMO's, respectively. The optimum values of L/FA + S and C/FA + S for Soil L are all between 3.25 and 3.5 percent, and the values for Soil M are between 1.75 and 2 percent. Comparing the results obtained for unconfined compressive strength (*2*) (Soil L: 3.5 percent, Soil M: 2.0 percent) confirms the MR-based findings and provides almost the same conclusions (using upper limits). Use of Equation 1 for Soil A yields a result of 2.63 percent for L (or C)/FA + S. The figure of 2.6 percent that can be drawn from the results of Figure 2 conforms satisfactorily with the figures previously referenced and supports the suitability of the PI-interpretation method. The FAMO for Soil A in various ratios is known, and Table 4 shows the ideal combinations for modified fly ash as 1.5 and 2.0 times the FAMO. For this method of calculation, see the procedures above for the PI-interpretation method. Thus the acceptable combinations are a ratio of 4 for F/L or F/C with an FA′ of 1.5 times the FAMO (FA = 13.2 percent, L or C = 3.3 percent, soil = 100 percent), or a ratio of 6 (F/L or F/C) with an FA′ of 2.0 × FAMO (FA = 22.3 percent, L or C = 3.7 percent, soil = 100 percent). The recommended combinations were incorporated in the design of test Road A.

Representation of MR Design Value

According to multilayer elastic criteria, MR values must be incorporated in the design in accordance with the relevant monthly

TABLE 4 Ratio and Amount of FA′ Combination

Ratio	1.5×FAMO		2.0×FAMO	
	FA′/S	C/FA+S	FA′/S	C/FA+S
2	12	3.7 ▲	16	4.8 ▲
4	16.5	2.9 ○	22	3.7 ▲
6	19.5	2.4 ▼	26	3.0 ○
8	21	1.9 ▼	28	2.5 ▼
10	22.5	1.7 ▼	30	2.1 ▼

▲: too high, not recommended; ▼: too low, not
○: acceptable combination

moisture figures when calculating the appropriate thickness for the pavement structure. Hence an initial appraisal of the test results from this study was necessary as a basis for pavement-thickness design.

For FA′ treated soils, where MR values and the σ_d used are concerned, the tire-pressure induced deformation should, as a rule, be within tolerance at a base-line σ_d of 41.4 and 82.8 kPa. Figure 2 shows that the MR values are approximately the same, allowing for some slight but tolerable differences. As stated previously, stability is excellent under unsaturated conditions. To ensure that conservative design figures are implemented, upper (unsaturated) and lower (saturated) limits should be established for design values. An overall analysis of Figure 2 reveals that 172.5 MPa (25 ksi) and 138 MPa (20 ksi) should be rational and somewhat conservative values for these three soils. Hence an MR value of 172.5 MPa is recommended for normal months and 138 MPa for wet months.

TEST ROAD

Design, Layout, and Arrangement of Test Road A

The pavement thickness was selected and designed for the test road on the basis of MR values. The layer-thickness design was varied in separate sections to evaluate the gravel equivalent factor value. (The layer coefficient of treated subgrade will be discussed further in a future study.) The details of the layout and arrangement are shown in Figure 3. Construction of the test road was completed in March 1989, and the field-investigation program was performed 2 years later.

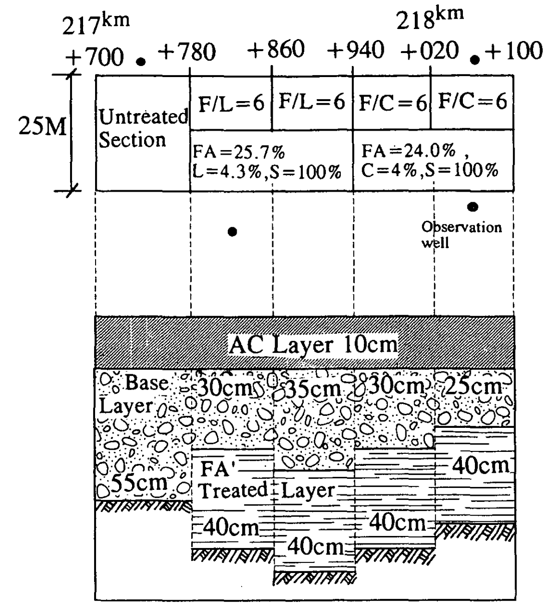

FIGURE 3 Arrangement thickness layout of Test Road A.

Field Investigation Program and Results

A series of survey and evaluation operations began after the test road had been open to traffic for 2 years. Because of the space limitations of this paper, only evaluations for data related to the FA′-treated subgrade layers will be presented. The pH values for the treated layer are listed in Table 5, along with those measured for the treated layer during mixing in the construction process. Table 5 shows pH values decreasing over time, which is explained by the chemical mechanisms of soil stabilization. The pozzolan reactions use hydroxyl (OH) ions to form stable bonds, thus they are unavailable in the pore water, resulting in lower pH values. During the investigation program, field CBRs were conducted, and the results are tabulated in Table 6. From this table it can be seen that for the treated layer satisfactory performance was achieved because the strength increased by a factor of 10 to 15. The lowest layer of untreated subgrade had CBR values that were too low, most likely because of groundwater effects.

When the CBR program was completed, the treated layer was cut into large blocks, which were moved from the test pit to the laboratory. These specimens were cut into small blocks with a rock saw and finished to a final size [D = 5 cm (1.5 in.), H = 10 cm (3.94 in.)] with a knife and sandpaper. The trimmed specimens were then placed into the MR testing device. Because these specimens were extremely difficult to trim, only one set of tests was conducted for each section. Typical results are shown in Figure 4, along with the MR values for untreated samples. It is evident from Figure 4 that treatment was effective. The recommended design values (20 to 25 ksi), drawn from the results of indoor testing, were confirmed as being satisfactory. The slightly low performance of the first two sections may be attributed to the disturbance of the sampling and trimming processes. In summary, synthesis of the above items of field data confirms that Class F fly ash with cement (or lime) added produces satisfactory results as a stabilizer of these subgrade soils. Great confidence is justified in this method of dealing with the fly ash disposal problem. The results of another area of research, the microstructure study, are further indicative of fly ash stabilization.

MICROSTRUCTURE EXAMINATION RESULTS

This portion of the project included investigation of the microstructure of laboratory-made and field specimens. To facilitate comparison and explanation, the microstructures of laboratory-made spec-

TABLE 5 pH Values for Soil A for Test Sections

Location	217^{km} +740 (Untreated)	217^{km} +820 (Treated)	217^{km} +900 (Treated)	217^{km} +980 (Treated)	218^{km} +060 (Treated)
During Construction	7.3~7.5 (Untreated)	11.40~11.51	11.57~11.71	11.68~11.78	11.45~11.60
36 months	Untreated	9.48	9.50	9.68	9.59
40 months	Untreated	8.93	8.51	8.92	8.65

TABLE 6 Field CBR Test Results (Percent)

Location	217^{km} +740 (Untreated)	217^{km} +820 (Treated)	217^{km} +900 (Treated)	217^{km} +980 (Treated)	218^{km} +060 (Treated)
Treated Layer	None	84.8	53.5	108.7	123.0
Untreated Layer	15.0	4.2	4.1	4.7	7.2

imens for Soil L, Soil M, and Soil A are presented in Figure 5. Because Soil L consists of heterogeneous basic materials, it develops an anisotropic structure under influence of water pressure [Figure 5 (*a*)]. Soil M appears to induce marked erosion of the fly ash, so it forms consolidation of the mudstone quickly [Figure 5 (*b*)]. Figure 5(*c*) shows that Soil M is dense in texture, hard, and bonds effectively (although cementing materials were distinct); newly developed faces effectively filled the fissures. Soil A is dense in texture; newly developed mineral faces consist of white encapsulated matter [Figure 5(*d*)]. The field samples for Soil A are shown in Figure 6. The items observed as results shown in Figure 5 are synthesized for comparison in Table 7.

Samples activated with cement (obtained from 217 km + 980 and 218 km + 060) were stronger in terms of mechanical properties and external appearance; they also presented a denser surface structure. In viewing these samples, one would notice a comparatively uniform appearance on cutting the surface open with a knife and a cross section that revealed a more uniform grain structure. Under observation with the microscope, as in Figure 5, the cementing materials presented tightly cross-linked interfaces in spite of their prominence, and the fly ash was joined strongly to the clay particles in its three-dimensional surroundings. These presented the densest structures of all the samples. Anisotropic arrangements resulting from traffic loading were observed in some cross-sectional views. Furthermore, newly developed mineral faces, consisting of white encapsulated matter and trichome effectively filled the cracks along which they had developed, acting as excellent cementing agents (Figure 5).

Although the samples activated with lime in Figure 5 were strong in texture, surface clumps which had formed showed a tendency to peel off. Voids of approximately 30 to 60 μm existed between these clumps of grains. Their outer appearance and mechanical properties were similar to those of the samples activated with cement, and low clay content made the

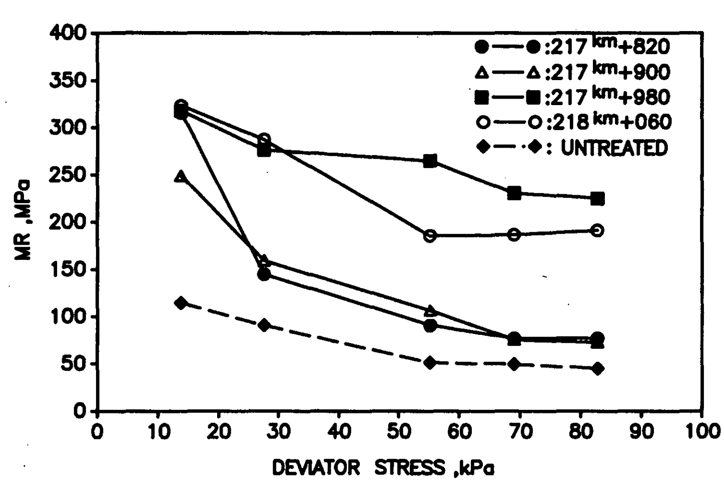

FIGURE 4 MR test results for specimen obtained from field.

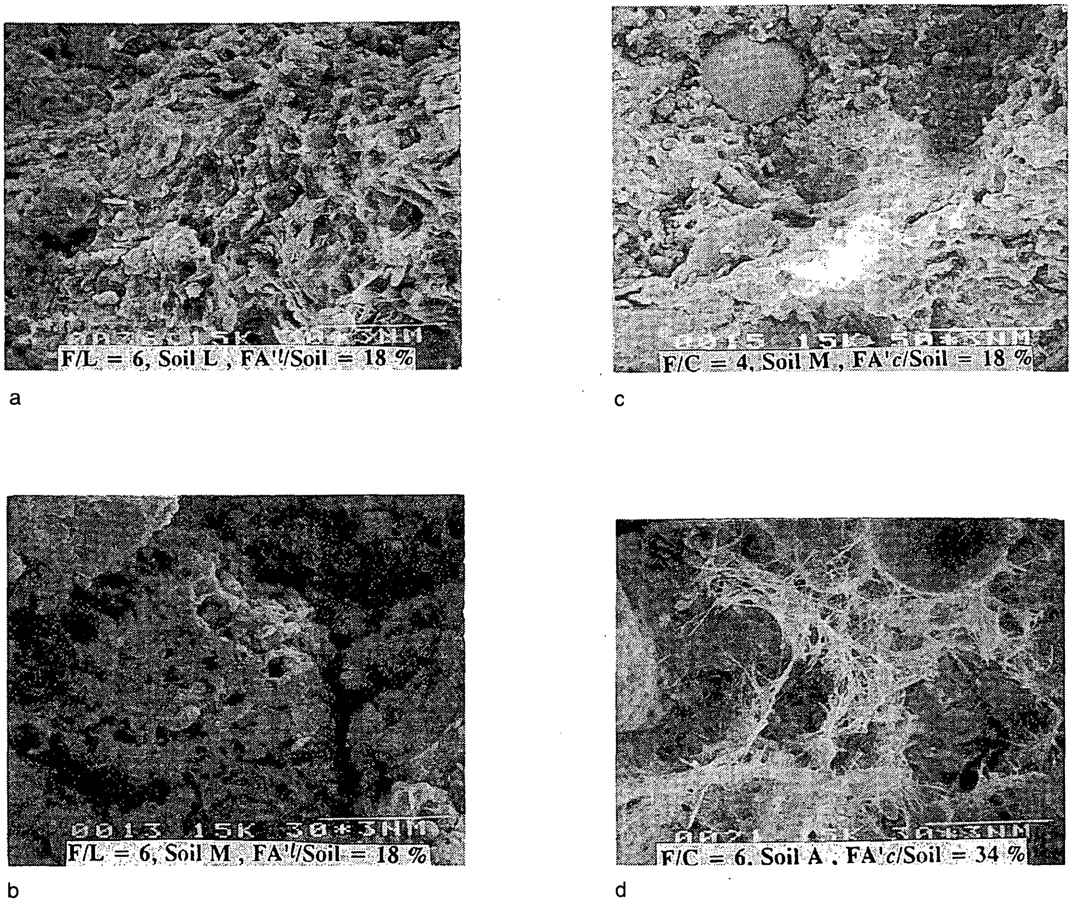

FIGURE 5 Microstructure from laboratory-made treated specimen.

grains clearly visible. The fly ash was not evenly mixed with the soil in these cases, and occasional large clumps were observed. The honeycomb structure that can be seen in the untreated soil was also observed in these samples, but in much lower proportions. From Figure 6 (*a*) and (*b*) it is evident that in terms of external appearance and unity, soils treated at the F/L ratio of 6 fell slightly short of the samples presented in Figure 6 (*c*) and (*d*), which had a cement additive. It is noted that the soils depicted in Figure 6 (*c*) and (*d*), which had an F/C ratio of 6, have formed more newly developed mineral faces (trichome and white portions). The characteristics are slightly anomalous for samples of Soil A with FA′ added at the ratios of F/C = 6 and F/L = 6. Both lime and cement appear more equal at an age of 4 years, which is what would be expected, because the cement will provide earlier strength gain and lime long-term strength gain.

CONCLUSION

On the basis of results from feasibility and applicability evaluations, this study was planned and conducted with a goal of simplifying design procedures and general applicability. The relevant results and conclusions for the materials tested in the test-road program are as follows:

- The PI-interpretation method recommended for ascertaining the optimum percentage of additives and fly ash for these soils has been verified by the compatible results obtained through MR testing.
- A cement additive, as revealed in the microstructure study of 40-month-old specimens, is superior to lime, which is what would be expected because the cement will provide earlier strength gain and lime long-term strength gain.
- Microscopic analysis confirms that the addition of lime or cement to Class F fly ash effectively induces beneficial reactions and significant improvements in strength and MR.

ACKNOWLEDGMENTS

This has been an extensive and long-term project in which too many people have participated to allow individual mention. The author expresses his appreciation to all concerned. The author also expresses his gratitude to the assistants and coordinators of the Taiwan Highway Bureau and to the Taiwan Electric Company, which provided funding, support, and the assistance of relevant personnel.

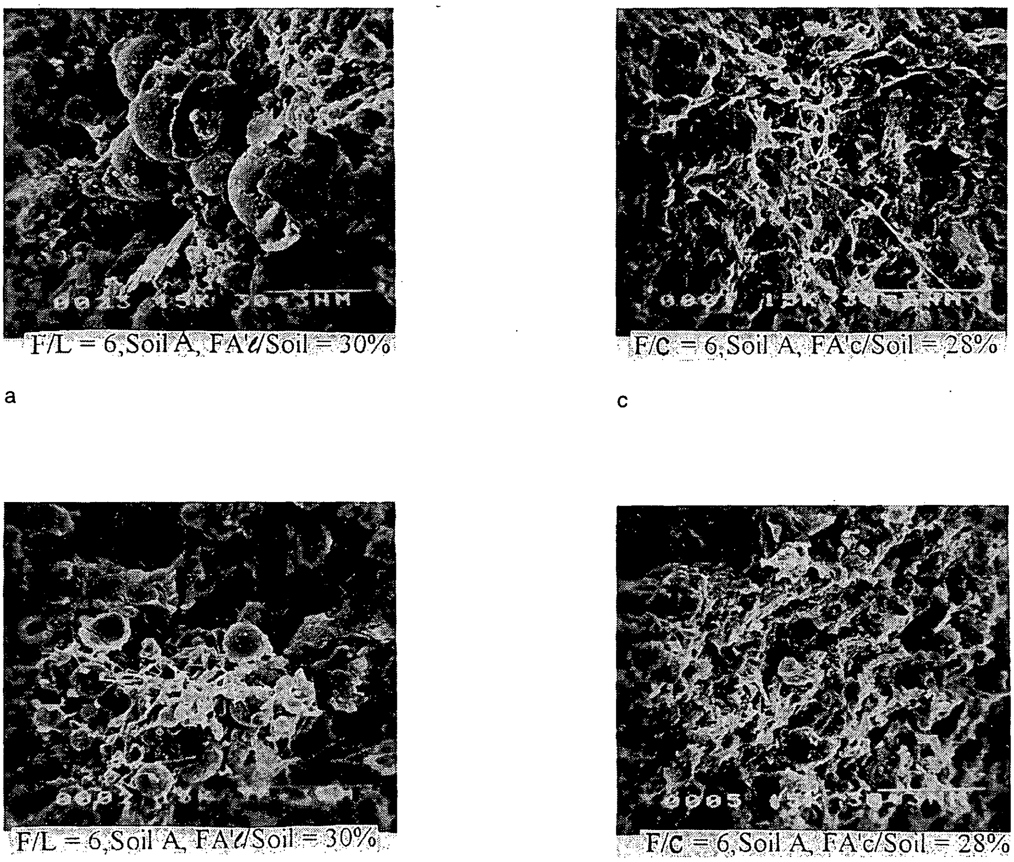

FIGURE 6 Microstructure from field-treated specimen.

TABLE 7 Microstructure Analysis of Various FA′ (FA′*l* or FA′*c*) Treated Soils

	Cementing (solid particles)		Material	Silt		Fine	Cementing	Pores		General
						<10μm	Agent	caves	fissures	
	outer shape	curvature	size difference	degree of sphericity	bundles					
Soil L	prominent	good	uniform	-------	-------	relatively few	poorly developed	many	many	insufficient density
Soil M	developed	good	not uniform	distinct	distinct	observable	full developed	present	few	extremely dense
Soil A	developed	good	uniform	distinct	observable	few	easily observable	many	present	acceptable
Soil A (field specimem) FA'l or FA'c	developed	good	not uniform	prominent	observable	relatively many	abundant	many	present	poor

REFERENCES

1. Chang, T. T., and K. Yu. *Study on Lime and Class F Fly Ash Stabilization for Linkou Lateritic Soils.* (in Chinese) Report NSC 74–0414–Po033–01, National Science Council, Taipei, Taiwan, R.O.C., 1986.
2. Eades, J. L., and R. E. Grim, A Quick Test to Determine Lime Requirements for Lime Stabilization. In *Highway Research Board Record 139,* HRB, National Research Council, Washington, D.C., 1963, pp. 61–72.
3. Sabry, M. M. A., and J. V. Parcher. Engineering Properties of Soil-Lime Mixes. *Journal of Transportation Engineering,* Vol. 105, No. 1, ASCE 1979, pp. 59–70.
4. *Standard Method for Wetting and Drying for Tests on Compacted Soil-Cement Mixtures.* Report D559–82, Part II. American Society for Testing and Materials, Philadelphia, Pa., 1982.
5. Chang T. T., and C. Y. Chang. *Application of Class Fly Ash for Subgrade Stabilization in Taiwan (II)—Test Road.* Final Report. Chung Yuan University, Chung Li, Taiwan, R.O.C., 1989.
6. Chang, T. T., C. Chiung, and C. Y. Chung. Modified Testing Device to

Evaluate MR Properties of Fly Ash Treated Subgrade Soils. *Geotechnical Testing Journal,* ASTM., 1991.

7. Chang, T. T., and Y. H. Liu. Resilent Modulus Property of Fly Ash Treated Fine-Grained Subgrade Soils. *Journal of the Chinese Institute of Civil and Hydraulic Engineering,* Vol. 4, No. 3, 1992, pp. 205–213.
8. *AASHTO Materials: Methods of Sampling and Testing.* American Association of State Highway and Transportation Officials, Washington, D.C., 1983, pp. 1157–1177.
9. *Soil Stabization Manual,* Vol. II FHWA, U.S. Department of Transportation, 1979.
10. *Soil Manual for Design of Asphalt Pavement Structures.* MS–10. The Asphalt Institute, Md., March 1978, pp. 133–147.

Publication of this paper sponsored by Committee on Cementitious Stabilization.