ACOUSTIC-EMISSION KAISER EFFECT IN FLY-ASH CEMENT MORTAR UNDER COMPRESSION

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ABSTRACT: Acoustic-emission (AE) technology is considered a potential new testing method to monitor the integrity of concrete materials. This study is devoted to the investigation of the AE Kaiser effect in fly-ash cement mortar (FACM) under uniaxial compression. The major experimental parameters include the amount of cement replaced by fly ash, curing time, compressive strain and stress, loading pattern, and loading rate. The test results showed that the AE Kaiser effect existed in FACM specimens up to 80% of its ultimate strength. Good correlation between the variation of the AE signals and the compressive strains was observed. In addition, the results indicated that the AE Kaiser effect existed in FACM specimen during different curing periods of three, seven, 14, and 28 days. These observations suggested that the AE Kaiser effect has good potential to be used as a new tool to monitor the loading history of concrete materials.

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INTRODUCTION

Acoustic emission (AE) can be described as the transient elastic waves resulting from local internal microdisplacement within a material (Nichols 1976; Malhotra and Carino 1991). The technology of acoustic emission is a relatively new testing method that has a high sensitivity for detecting active microscopic events (such as microcracking, dislocation movement, phase transformation or debonding, etc.) within a material. These events lead to the rapid release of the internal strain energy in the form of high-frequency elastic waves and result in detectable AE signals (Matthews 1983; Miller and McIntire 1987). For civil engineering application, owing to its real-time and highly sensible detectability, much effort has been devoted to the research of this new technology to assess the integrity of concrete structures (Robinson 1965; Alliche and Francois 1986; Ohtsu 1987; Rossi et al. 1989).

In the early 1950s, German scientist Kaiser discovered that the AE activity of many materials is irreversible during the unloading and reloading process, i.e., AE signals are not produced until the previous maximum load is exceeded (Kaiser 1953). This irreversible phenomenon is called the "Kaiser effect." Since the AE Kaiser effect may provide information on the previous maximum load a structural member has been subjected to, it may become a useful tool to estimate the deteriorated level and the degree of safety of structures in service.

To utilize AE as a diagnostic tool to monitor the deterioration of concrete structures, the AE Kaiser effect on concrete materials should be studied first. Among the concrete materials employed today, the use of fly ash concrete has become increasingly popular. This is because a suitable addition of fly ash can improve the workability, compressive strength, and durability of concrete (Mehta 1983; Robert and Fredrik 1990). In addition, since fly-ash cement mortar (FACM) is the basic component of fly-ash concrete, it is believed that an investigation focusing on the Kaiser effect of FACM may provide basic information to further understand the Kaiser effect in concrete materials.

A literature survey made by the writers showed that during the past two decades, different conclusions were reached on the existence of Kaiser effect in concrete materials. Some of the conclusions made by previous researchers include: (1) The Kaiser effect exists in concrete materials up to 80% of its ultimate compressive strength (McCabe et al. 1976; Niiseki et al. 1986; Uomoto 1987; Lim and Koo 1989; Weng et al. 1992); (2) this effect is highly dependent on the length of the unloading period, i.e., the existence of Kaiser effect in concrete materials is a temporary phenomenon (Nielsen and Griffin 1977); and (3) the Kaiser effect does not exist in concrete materials (Li and Poorooshasb 1986). Considering these different conclusions on the Kaiser effect in concrete materials, the writers observe that the difference may be caused by the following uncertainties: (1) The variations in the loading condition and curing period of the concrete materials; and (2) the possible continuation of cement hydration, which may repair some of the microcracks within the concrete materials. Therefore, it is felt that further investigation on the Kaiser effect in concrete materials subjected to a different loading condition and curing period would be necessary.

The purpose of this research is to investigate the AE Kaiser effect in FACM under uniaxial compression. In this study, the amount of cement replaced by fly ash, curing time, compressive strain and stress, loading pattern, and loading rate are the major parameters of FACM related to the Kaiser effect. Results of the influence of these parameters on the Kaiser effect are reported and discussed in this paper.

AE INSTRUMENTATION

A schematic illustration of the test setup is shown in Fig. 1. An AET 5500 monitoring system was used in this study. The AE signals emitted from a FACM specimen during the test were detected by a AE sensor with resonant frequency at 175 kHz. A preamplifier with 60 dB gain was used and the

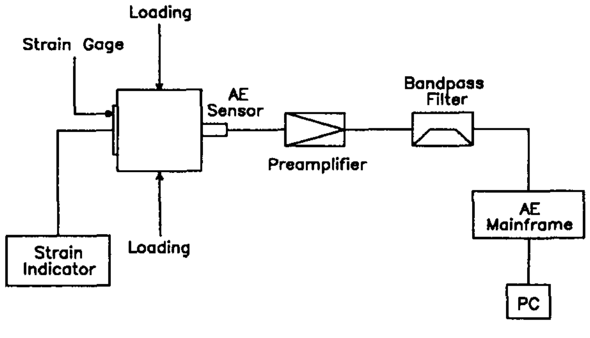

FIG. 1. Block Diagram of AE Setup for Study of AE Kaiser Effect in FACM under Uniaxial Compression

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main amplifier was set at 30 dB, which gave a total gain of 90 dB. In addition, a band-pass filter with a frequency range between 125 and 250 kHz was used. To eliminate the effect of background noise, the threshold level for AE detection was set to 40 dB. During the tests, the AE sensor was carefully attached to the same location of each specimen to maintain a consistent experimental condition throughout the tests.

MATERIALS AND TEST SPECIMENS

The FACM specimens used in this study were composed of Class F fly-ash, Type I portland cement, and ASTM graded standard sand for compressive strength test [ASTM C109-86, "Standard" (1986)]. The water to cement ratio was 0.5, and the ratio of cement to sand was 1:2.75. The specimens were 50 × 50 × 50 mm cubes. Table 1 gives the number of specimens tested for each combination of the major FACM parameters; a total of 84 specimens was tested. The amount of cement replaced by fly-ash varied from 0% to 50%. For the study of the influence of the amount of cement replacement, compressive strain and loading pattern on the AE Kaiser effect, six specimens were used for each combination of the cement replacement. For the study of the influence of the curing time (three, seven, 14, and 28 days) and loading rate (7.5, 15, 30, and 45 kN/min) on the AE Kaiser effect, 16 specimens were tested for each combination (0, 20, and 40%) of the cement replacement.

EXPERIMENTAL PROCEDURE

To study the influence of the amount of cement replacement, compressive strain and loading pattern on the AE Kaiser effect of 28-day FACM specimens, the following experimental procedure was used:

1. After curing for 28 days, the specimens were removed from the curing room and kept to dry naturally in the air for about 2–3 hr.
2. A strain gauge was glued to the specimen surface.
3. The AE sensor was attached to the specimen surface with an acoustic impedance matching couplant.
4. The AE monitoring system, the strain indicator, and the loading pattern were set up.
5. The test was started. The AE signals and strain readings were recorded.
6. To study the AE Kaiser effect, the load was first increased to 20 kN and was held at this level for about 3 min, then unloaded to 5 kN.
7. After holding the load at 5 kN for about 1 min, the load was increased to 40 kN. The load was held at this level for about 3 min, then unloaded to 5 kN again.
8. The reload-unload process was repeated for higher loads of 60, 80, or 100 kN until failure of the specimen occurred.

In addition, to determine the maximum compressive strength $(f_c)_{ke}$ for which the AE Kaiser effect exists in the FACM specimens, a reload-unload process was used. The procedure to determine the value of $(f_c)_{ke}$ is described as follows:

1. The average ultimate compressive strength f'_c for each type of FACM specimen has to be found.
2. The specimen was then loaded to a load level of $L_{0.6}$, which is the load required to produce a stress of $0.6f'_c$ of the specimen. Then, the load was held at this level for 3 min before it was unloaded to 5 kN.
3. Holding the load at 5 kN for about 1 min, the specimen was reloaded to the load level of $(L_{0.6} + 1)$ kN. After the load was held at this level for 3 min, it was unloaded to 5 kN again.
4. The reload-unload process was repeated to the next higher load (with 1 kN added for each step) until the disappearance of the Kaiser effect in the specimen was observed. The highest load observed is considered the maximum load $(P_c)_{ke}$ for which the Kaiser effect exists in the test specimen.
5. Finally, the maximum compressive strength $(f_c)_{ke}$ was found by dividing the maximum load $(P_c)_{ke}$ by the cross-section area of the specimen.

To study the influence of curing time and loading rate on the AE Kaiser effect, the following experimental procedure was used:

1. After curing for 3 days, the specimens were removed from the curing room and kept to dry naturally in air for about 2 to 3 hr.
2. The AE sensor was attached to the specimen surface with an acoustic impedance matching couplant.
3. The AE monitoring system and the loading rate (7.5, 15, 30, or 45 kN/min) were set up. The test was started and AE signals were recorded.
4. When the load was first increased to 10 kN, it was held at this load level for about 3 min, then released.
5. The tested specimen was recured immediately. After curing for 7 days, procedures 1–3 were repeated.
6. The load was increased to 10 kN and was held at this level for about 3 min, then was unloaded to 5 kN.
7. After holding the load at 5 kN for about 1 min, the load was increased to 20 kN. The load was held at this level for about 3 min, then released.
8. The tested specimen was recured immediately. After curing for 14 days, the unload and reload processes of 5–7 were repeated, but the load was gradually increased to 40 kN.
9. The tested specimen was recured immediately. After curing for 28 days, the unload and reload process of 5–7 were repeated, but the load was gradually increased to 80 kN.

EXPERIMENTAL RESULTS AND COMMENT

AE Kaiser Effect in FACM Specimens

Figs. 2(a)–(d) show four typical AE Kaiser effects observed in FACM specimens with different amounts of cement replacement. In these figures, at the beginning of each test, very high AE count rates appeared; here, the count rate is defined as the number of AE counts detected within a duration of 5 s, and the number of AE counts is defined as the number of times the AE signal exceeds a preset threshold (Miller and McIntire 1987). When the applied load (depicted

TABLE 1. Number of Specimens for Study of AE Kaiser Effect in Fly-Ash Cement Mortar under Uniaxial Compression

Subjects of study	Influence of amount of cement replacement, compressive strain, and loading pattern on AE Kaiser effect						Influence of curing time and loading rate on AE Kaiser effect		
Amount of cement replaced by fly ash	0	10%	20%	30%	40%	50%	0	20%	40%
Number of specimens	6	6	6	6	6	6	16	16	16

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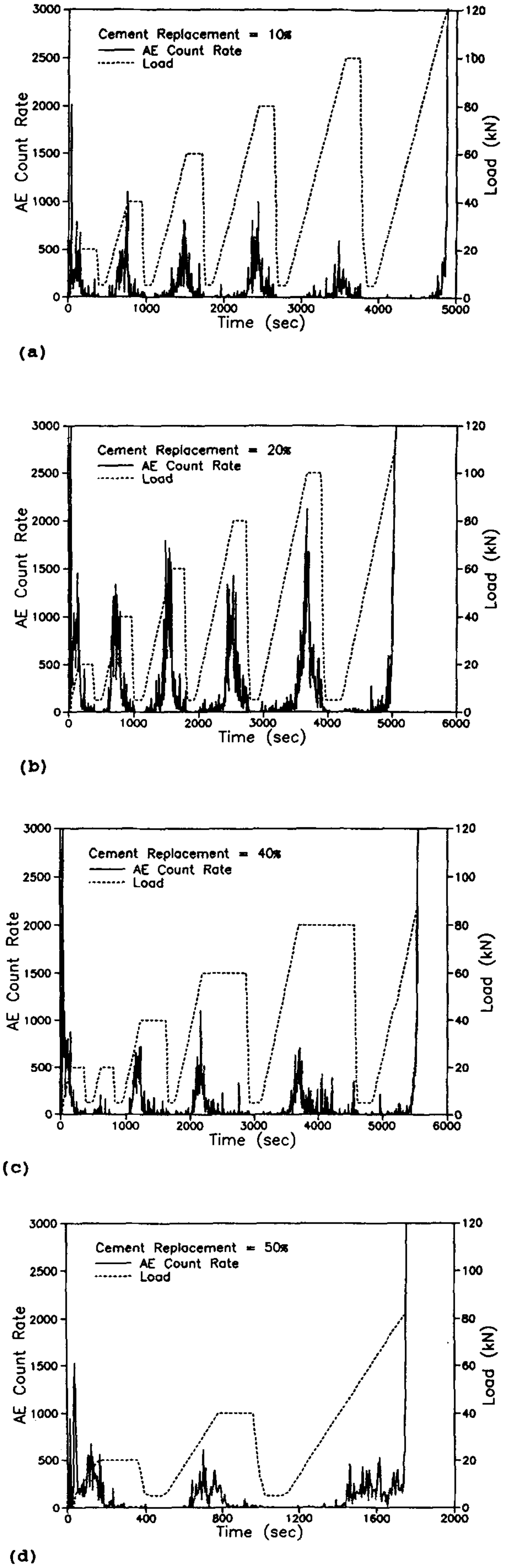

FIG. 2. AE Kaiser Effect in FACM Specimen with: (a) 10% Cement Replacement; (b) 20% Cement Replacement; (c) 40% Cement Replacement; (d) 50% Cement Replacement

by the dotted line) was held at a constant level of 20 kN for a short time (about 3 min), the AE count rate was found to decrease rapidly. The disappearance of the AE count rate indicated that the cracks within the specimens had stopped growing. During the unload and reload process, the load was first released to 5 kN and then the specimens were reloaded to a higher load level of 40 kN. Figs. 2(a)–(d) show that the AE signals were rare when the applied load did not exceed the previous maximum load. The AE signals appeared again only when the applied load exceeded the previous maximum load. This phenomenon indicated that the AE Kaiser effect exists in FACM specimens.

In addition, when the applied load approached the ultimate compressive strength of each specimen, the AE count rate was found to increase sharply. This means that the cracks within the specimen were growing quickly and the specimen was in an unstable condition.

Based on the aforementioned phenomenon, it is felt that a study on the maximum compressive strength for which the AE Kaiser effect exists may provide further insight into the behavior of the AE Kaiser effect in FACM. Table 2 shows the experimental results of the maximum compressive strength for which the AE Kaiser effect exists in FACM specimens. In this table, $(f_c)_{k_e}$ is the maximum compressive strength for which the AE Kaiser effect exists in a FACM specimen. Along with the investigation on the existence of the AE Kaiser effect in FACM, Fig. 3 shows the correlation between the maximum compressive strength for the existence of the AE Kaiser effect and the amount of cement replacement in FACM specimens. The figure shows that although the amount of cement replacement varies from 0% to 50%, the observed maximum compressive strength for which the AE Kaiser effect exists in FACM specimens was approximately 80% (varying from 75 to 85%) of its ultimate compressive strength. Thus, the foregoing observation indicated that the AE Kaiser effect exists in FACM up to the strength level of approximately 80% of its ultimate compressive strength.

AE Kaiser Effect versus Compressive Strain

Fig. 4 shows a typical correlation between the AE "total events" and the measured compressive strains of a FACM specimen. The AE total events are the accumulated total number of AE events detected, where an AE event is defined as a local materials change or microdisplacement, which results in an individual AE signal burst (Miller and McIntire 1987). This figure shows that during the first two-third of the loading process, both the AE total events and the compressive strains increased approximately linearly and were maintained at a relatively low level. However, when the specimen was approaching its ultimate strength, both the AE total events and the measured compressive strains were found to increase rapidly and nonlinearly. The aforementioned correlation also existed between the variations of the AE count rate (number of AE count detected within a duration of 5 s) and the measured compressive strains, as shown in Fig. 5.

Fig. 6 shows a typical correlation between the AE Kaiser effect and the measured compressive strains from the unload and reload process of a FACM specimen. In Fig. 6, the loading steps A to D, where the AE Kaiser effect existed in the FACM specimen, the compressive strains increased moderately as the load was held at a constant level. However, when the applied load approached the ultimate compressive strength of the specimen (step E), the compressive strains were found to increase sharply. At this stage, the AE Kaiser effect did not exist in the FACM specimens.

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TABLE 2. Maximum Compressive Strength for which AE Kaiser Effect Exists in FACM Specimens

Amount of Cement replacement (%) (1)		0 (2)	10 (3)	20 (4)	30 (5)	40 (6)	50 (7)
Specimen number 1	$(f_c)_{ke}$ (MPa)	33.8	34.8	35.8	35.4	30.4	24.4
	f'_c (MPa)	39.7	42.3	45.7	42.2	38.3	32.1
	$[(f_c)_{ke}/f'_c]$ (%)	85.0	82.4	78.2	83.8	79.4	76.1
Specimen number 2	$(f_c)_{ke}$ (MPa)	34.3	37.0	35.9	35.2	28.2	24.8
	f'_c (MPa)	41.3	44.7	44.6	42.8	36.1	33.2
	$[(f_c)_{ke}/f'_c]$ (%)	83.0	83.0	80.6	82.1	78.3	74.6

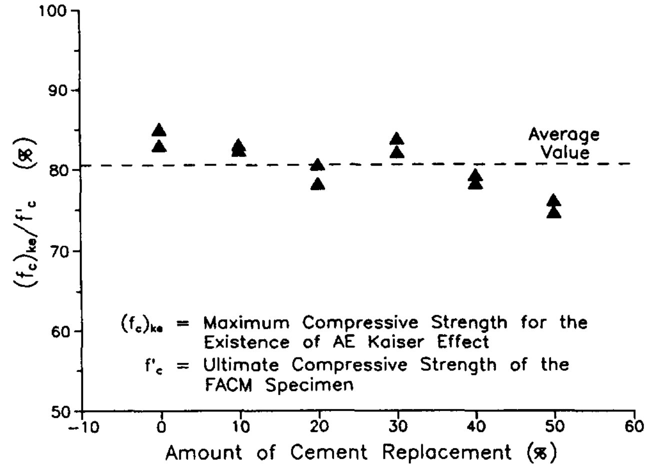

FIG. 3. Correlation between Compressive Strength for Existence of AE Kaiser Effect and Amount of Cement Replacement in FACM Specimens

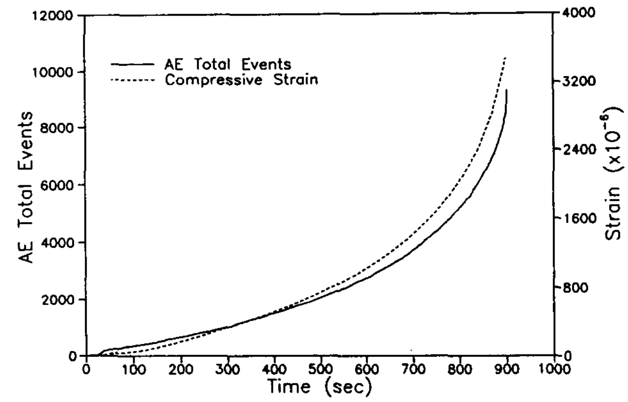

FIG. 4. Correlation between AE Total Events and Compressive Strains of FACM Specimen (Age = 28 Days, Cement Replacement = 10%)

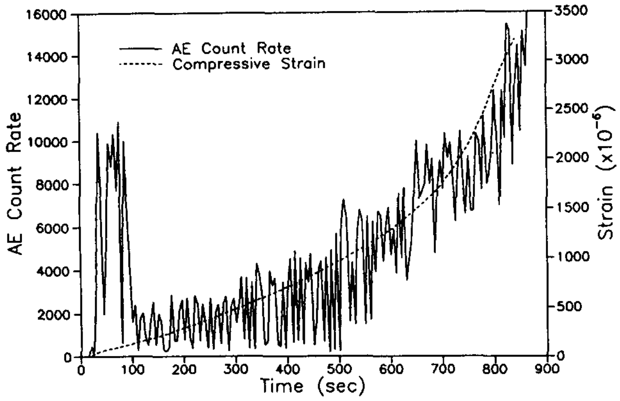

FIG. 5. Correlation between AE Count Rate and Compressive Strains of FACM Specimen (Age = 28 Days, Cement Replacement = 30%)

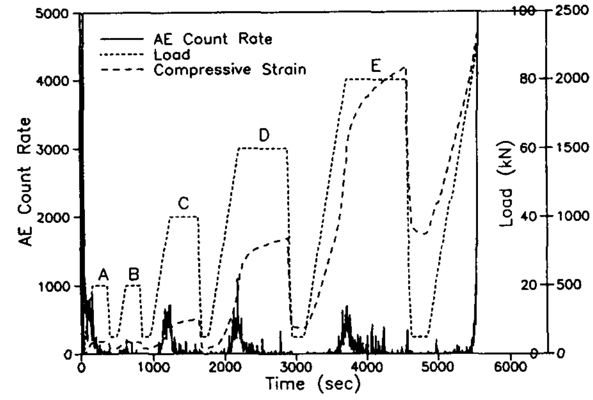

FIG. 6. Typical Correlation between AE Kaiser Effect and Compressive Strains of FACM Specimen (Age = 28 Days, Cement Replacement = 40%)

Influence of Loading Patterns on AE Kaiser Effect

Figs. 7(a) and (b) show the AE results of two FACM specimens tested with different loading patterns, A and B. Loading pattern A in Fig. 7(a) is similar to the loading patterns shown in Figs. 2(a)–(d). Loading pattern B in Fig. 7(b) indicates that during the unload-reload process, the applied load did not maintain a constant level before unloading. The results in Fig. 7(b) indicate that AE signals were rare when the applied load did not exceed the previous maximum load. However, many AE signals appeared when the applied load exceeded the previous maximum load. This phenomenon continued throughout the loading process until the load was increased to about 80% of the specimen's ultimate compressive strength.

In addition to the foregoing observations, Figs. 7(a) and (b) show that: (1) As compared with the loading pattern used in Figs. 7(a) and (b), the AE results showed that the AE Kaiser effect existed in FACM specimens regardless of the change in the loading pattern; and (2) the Kaiser effect existed in FACM specimens when the applied load was within about 80% of the specimen's ultimate compressive strength.

Influence of Curing Time on AE Kaiser Effect

Figs. 8(a)–(d) show the influence of the FACM curing time (three to 28 days) on the AE Kaiser effect. For the specimen tested at the seven-day age, Fig. 8(b) shows that at the beginning of the test, a high AE count rate was detected within a short period of time (usually less than 20 s). The reasons for the appearance of these AE signals may be clarified as follows: (1) AE signals resulted from the contact of the head of universal testing machine and the test specimen; and (b) AE signals resulted from the closure of small discontinuities or microcracks within the test specimen. As the loading pro-

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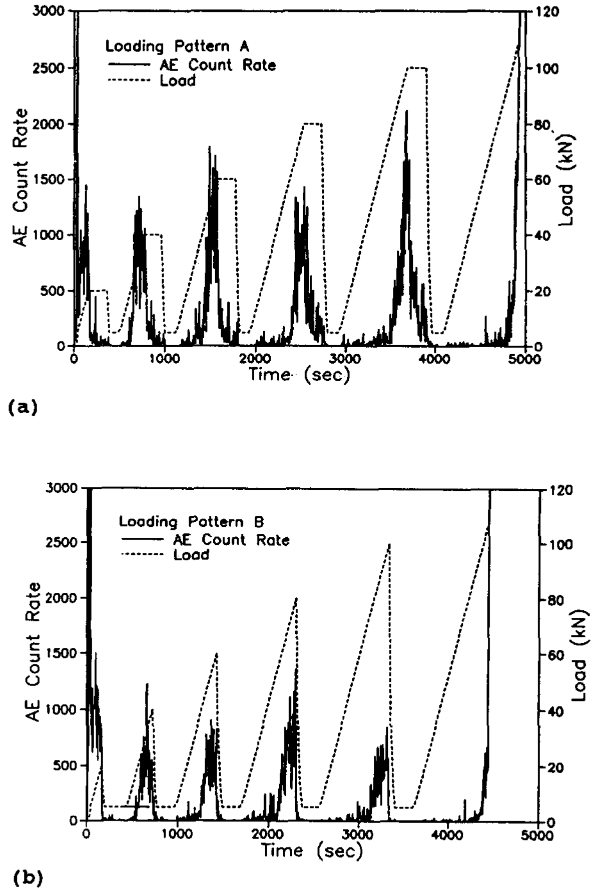

FIG. 7. AE Kaiser Effect for FACM Specimen (Age = 28 Days, Cement Replacement = 30%) Subjected to: (a) Loading Pattern A; (b) Loading Pattern B

cess continued, the AE signals were rare when the applied load did not exceed the previous maximum load, which was applied at the three-day age [as shown in Fig. 8(a)]. However, many AE signals appeared when the applied load exceeded the previous maximum load. A similar phenomenon was also observed during the unload-reload process of the same specimen tested at the 14-day and 28-day ages. These observations suggested that the AE Kaiser effect existed in FACM specimens during the curing periods of three, seven, 14, and 28 days.

The foregoing descriptions indicate that although the FACM specimen had been loaded several times during the curing periods of three to 28 days, the AE Kaiser effect still existed in the specimen. This experimental finding showed that the existence of the AE Kaiser effect in the FACM is independent of the curing time. This result suggested that the AE Kaiser effect has great potential for monitoring the FACM loading history.

Influence of Loading Rate on AE Kaiser Effect

To study the influence of the loading rate on the AE Kaiser effect, 24 specimens were tested at loading rate varying from 7.5 kN/min to 45 kN/min. Figs. 9(a) and (b) show typical results of the influence of the loading rate on the AE Kaiser effect of a FACM specimen tested at different curing times. The specimen in Fig. 9(a) had been preloaded to 20 kN at the three-day age; in Fig. 9(b), the specimen had been preloaded to 40 kN at the 14-day age. Figs. 9(a) and (b) indicate that AE signals were rare when the applied load did not exceed the previous maximum load. However, many AE signals appeared when the applied load exceeded the previous

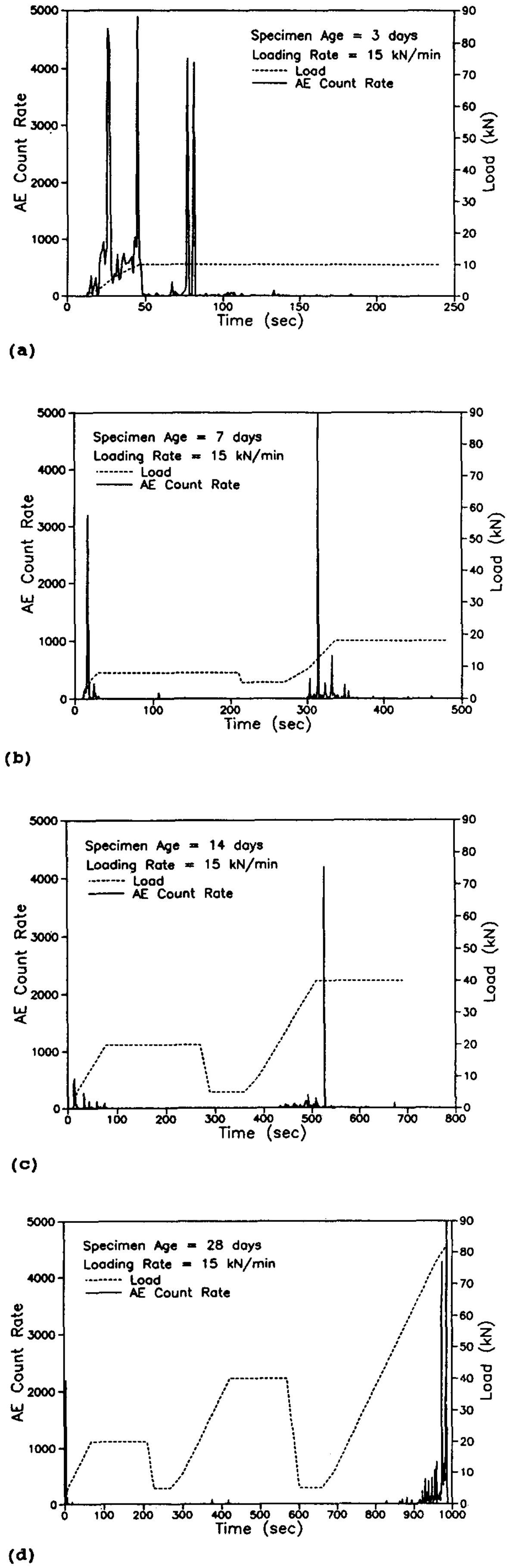

FIG. 8. Influence of FACM Curing Time on AE Kaiser Effect (Cement Replacement = 20%, Loading Rate = 15 kN/min): (a) Age = 3 days; (b) Age = 7 Days; (c) Age = 14 Days; (d) Age = 28 Days

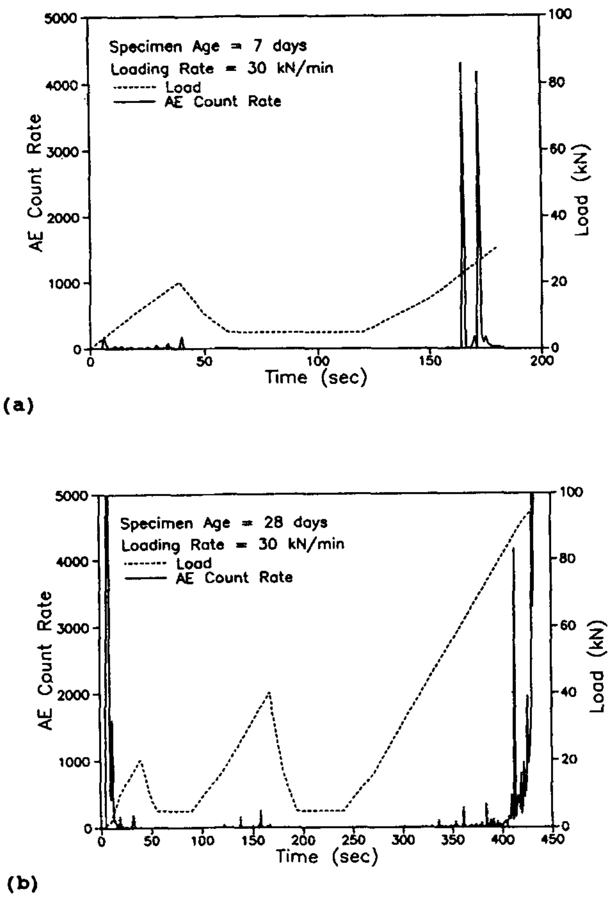

FIG. 9. Influence of Loading Rate on AE Kaiser Effect of FACM Specimen Tested at Different Curing Time (Loading Rate = 30 kN/min, Cement Replacement = 0%): (a) Age = 7 Days; (b) Age = 28 Days

maximum load. These phenomena indicated that the AE Kaiser effect still existed in the FACM specimen.

In addition, by comparing the AE results shown in Figs. 8 and 9, it is observed that: (1) In spite of the difference in the loading rate used in the tests (15 and 30 kN/min in Figs. 8 and 9, respectively), the AE Kaiser effect existed in the FACM specimens during the entire curing period; and (2) The AE Kaiser effect existed in FACM specimens regardless of the change in the loading rate varying from 7.5 kN/min to 45 kN/min.

SUMMARY AND CONCLUSIONS

Based on the experimental results of this study, the following conclusions are made:

The test results showed that the AE Kaiser effect existed in FACM specimens, with the amount of cement replacement varying from 0% to 50%. However, when the load level exceeded about 80% of the ultimate compressive strength of the FACM specimen, it was found that AE Kaiser effect did not exist any more.

The test results also indicated that the detected AE signals correlate well with the measured compressive strains in the FACM specimens.

In addition, the AE results showed that the AE Kaiser effect existed in FACM specimens regardless of the change in the loading pattern.

The results of the detected AE signals from the FACM specimens at different curing periods showed that the AE Kaiser effect existed in FACM specimens during the curing periods of three, seven, 14, and 28 days.

The test results indicated that the variation in the loading rate, from 7.5 kN/min to 45 kN/min, did not affect the existence of the AE Kaiser effect in FACM specimens.

The existence of the Kaiser effect in FACM specimens suggested that the AE Kaiser effect may potentially become a new tool to judge the loading history of fly-ash concrete materials.

Finally, it is hoped that this study would provide useful information for further investigation on the application of acoustic-emission technology on concrete materials.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

f'_c = ultimate compressive strength;
$(f_c)_{ke}$ = maximum compressive strength for which the AE Kaiser effect exists in the FACM specimen; and
$(P_c)_{ke}$ = maximum load for which the AE Kaiser effect existed in the test specimen.

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