

# Effects of Cyclic Wetting-Drying Weathering on Wear Resistance of Concrete Pavement

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This paper describes the development of a laboratory test procedure to assess the weathering effects of a wet tropical climate on wear resistance of concrete pavements. An accelerated weathering model was fabricated to provide cyclic wetting and drying treatment in a laboratory simulation of the weathering effects of Singapore's climate. The effects of weathering on wear resistance were evaluated by means of a rotating drum test conducted on plain cement mortar specimens with and without weathering treatment. The study showed that cyclic wetting and drying weathering significantly reduced the wear resistance of cement mortar test specimens. Although no correlation relationship is available at this stage between test data of the proposed procedure and field performance of in-service pavements, results obtained in this study suggest that the test procedure could find useful application in evaluating the relative surface wear resistance and durability of various concrete pavement materials.

The provision of a durable traveled surface is an important consideration in highway pavement design. Deterioration of pavement surfaces, such as raveling, spalling, and surface wear, although usually causing negligible loss in structural capacity of pavements, is a major concern to highway engineers. Such surface defects can seriously affect riding quality and may considerably reduce the useful service life of the pavement affected.

The task of providing a durable pavement surface is not an easy one. Highway pavements are exposed to environmental weathering throughout their service periods and are constantly subjected to repetitive wearing actions caused by moving vehicular traffic. Once a surface distress is initiated, by either traffic or environmental factors, both will act together to contribute to the continuing and, in many cases, accelerating deterioration of the pavement surface. A complete study of pavement surface durability would therefore require analysis of the impacts of both traffic loadings and environmental weathering.

On concrete pavements, according to Burwell (1), the following two types of wear mechanism are prominent. One is known as surface fatigue wear, which is caused by vertical dynamic wheel loads of vehicles. The other is abrasive wear, which causes damage through rubbing actions between tires and pavement surface and through scratching and gouging actions caused by particles caught between moving wheels and the road surface. This suggests that a meaningful surface wear evaluation of concrete pavement materials must include the effects of both wear mechanisms.

The study of damaging effects of environmental weathering

has been a topic of research for many decades (2, 3). This problem is complicated because outdoor exposure tests are time-consuming, and it is difficult to control and standardize test conditions. As a result, laboratory-accelerated tests are often employed to predict the in-service durability of various types of materials. A number of testing devices known as weatherometers are available in the commercial market (4). They are typically equipped for test cycles requiring alternate light-dark and wet-dry exposures with temperature and relative humidity controls. Regardless of the type of equipment used, a laboratory-accelerated test must be designed to simulate as closely as possible the in-service environment in which the test material is intended to be used, so as to produce results that correlate well with material performance under outdoor service conditions.

This paper describes a laboratory test procedure for evaluating the relative durability of concrete pavement materials against surface wear. A laboratory-accelerated weathering model was developed to simulate the wetting and drying cycles of a wet tropical climate. The effects of wetting and drying weathering on material surface wear resistance were then determined by means of a rotating drum wear test conducted on specimens with and without weathering treatment.

## BACKGROUND

Concrete pavements have been extensively used for bus bay, bus lane, and bus terminal construction in Singapore since the late 1970s. The switch from bituminous to concrete pavements was made after more than 20 years of unsatisfactory performance of bituminous pavements on roads dominated by bus traffic (5). The local experience with concrete pavements so far indicates that, although these pavements in general perform satisfactorily structurally, surface deterioration is a common distress problem that could drastically reduce the useful service life of those pavements affected.

The surface deterioration is characterized by loss of cement mortar from the road surface along wheel paths, thereby exposing coarse aggregates and giving the surface a rough and shabby appearance. The ride on such deteriorated surfaces is rough, noisy, and uncomfortable. Field observations indicated that the deterioration of concrete pavements involved initial wear of the hardened cement mortar at the surface. As the cement mortar was worn away, coarse aggregates were ultimately exposed. Depending on the bond between the cement mortar and coarse aggregates, the progressive wear could lead to raveling.

The present study is confined only to the first phase of the deterioration process, during which the wear resistance of cement mortar governs. This is important because a highway pavement that suffers deterioration of surface cement mortar is undesirable because it would not provide an acceptably smooth ride.

## TEST METHODOLOGY

The aim of the test program in this study was to develop a test procedure that could be used by local pavement designers and maintenance engineers in their evaluation of material quality and durability for new construction or resurfacing of concrete pavements. The laboratory test was conducted on 100-mm (3.937-in.) cubical specimens. The procedure developed was composed of two parts. First, specimens were treated with laboratory-simulated wetting and drying cycles. Next, surface wear resistance tests were conducted on treated and untreated specimens to evaluate their relative wear resistance. Basis and details of the two parts are described below.

## Weathering Simulation

The wet tropical climate of Singapore, as depicted in Figure 1, is characterized by an abundance of rainfall as well as bright sunshine and a relatively uniform temperature accompanied by high humidity throughout the year. The region generally has rainfall throughout the year but tends to be particularly wet during the monsoon season from November to January. The average annual rainfall is around 2,200 mm (86 in.), with precipitation of more than 50 mm a day occurring about nine times a year (6). The pavements in the region are also exposed to sunshine extensively each year. The annual average number of hours each day under bright sunshine is more than 5 hours. The abundance of both rainfall and sunlight results in a rel-

atively large number of wetting and drying cycles on the pavement surface. Precipitation falling on sun-heated pavements and intense sunlight drying up rain-soaked road surfaces are common scenes in Singapore.

On a tropical day, the maximum air temperature is around 31°C and the minimum 24°C. The surface temperature variation on most road pavements is much larger. Concrete pavement surface temperatures, measured by using thermocouple wires, usually range from around 25°C in the early morning to as high as 60°C on wheel paths on a hot afternoon. Thus, a wetting or drying process with a temperature change of 30 to 35°C is not unusual.

A laboratory model designed to provide alternating wetting and drying was used to simulate weathering caused by the frequent alternating rainfall and sunshine exposure of in-service pavements. The accelerated weathering model is essentially a concrete tank with an enclosed space that measured 915 mm (36 in.) in height and 940 mm by 1,420 mm (37 in. by 56 in.) in plane cross-section. Wetting of test specimens was achieved by spraying tap water, at about 28°C, through eight shower heads that were fitted on the interior walls of the weathering tank. The number of shower heads was more than sufficient to keep test specimens wet throughout the wetting phase. Heating during the drying phase was provided by four 500-W ceramic heaters located at the underside of the ceiling of the weathering tank. A surface temperature of 60°C was achieved on 100-mm concrete cube specimens placed on the floor of the tank, after about 100 minutes of exposure to heating in the tank.

This study adopted a 4-hour weathering treatment cycle that consisted of 2 hours of wetting followed by 2 hours of drying. The length of the wetting phase was selected to represent approximately the mean duration of rainfall in Singapore (6). The 2-hour drying period was chosen so as to attain the desired maximum temperature of about 60°C during the drying period. Due to high humidity in the weathering tank, the 2-hour drying treatment was, in terms of moisture

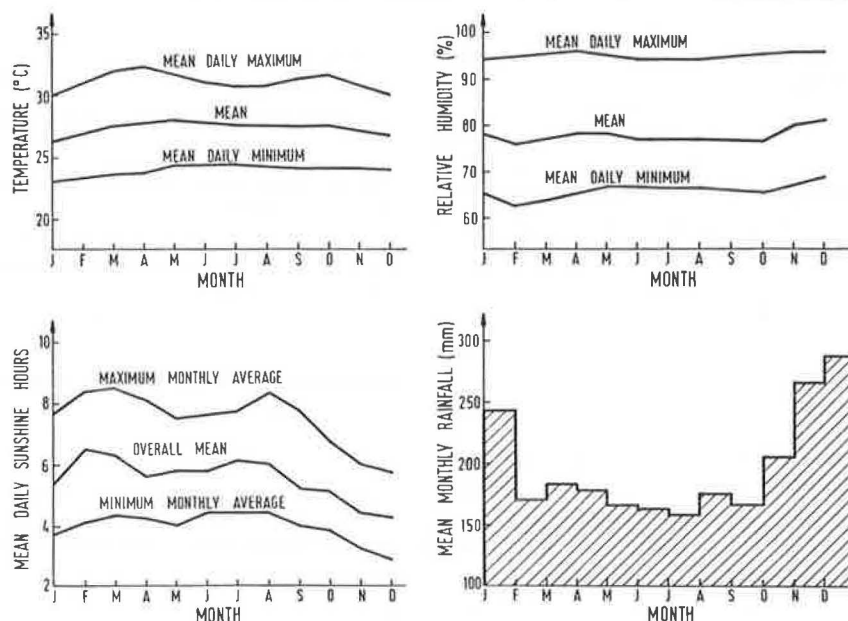


FIGURE 1 Characteristics of Singapore climate based on data from 1967–1986.

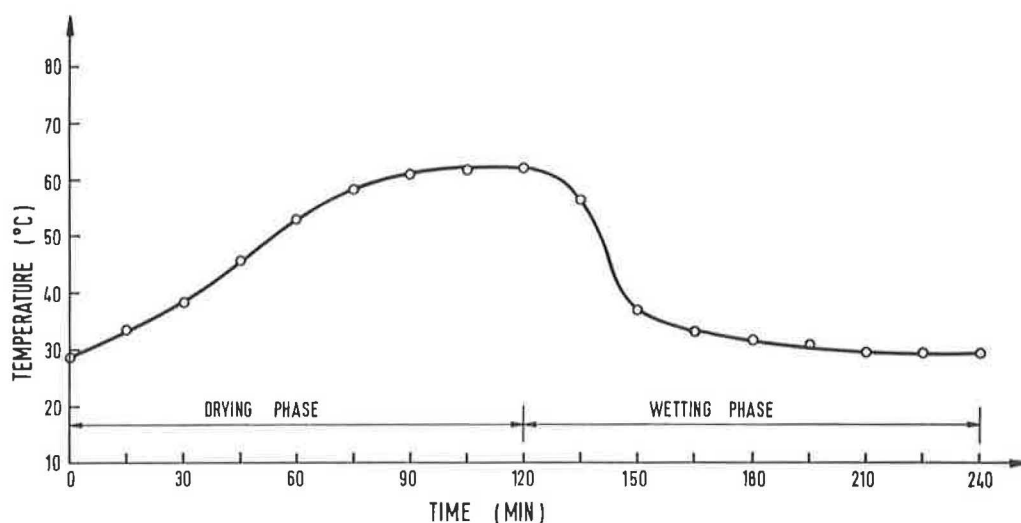


FIGURE 2 Surface temperature variations of cement mortar specimens in weathering model.

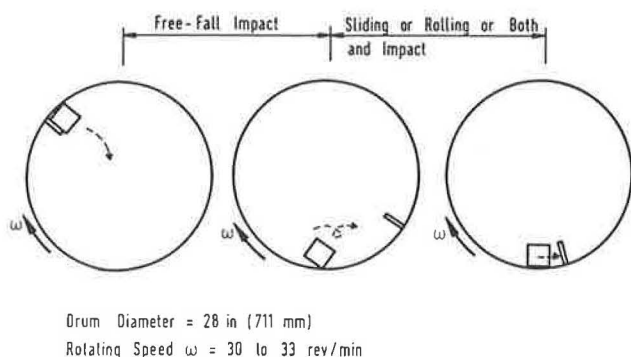


FIGURE 3 Schematic representation of wearing actions on a cubical specimen in a rotating drum test (7).

loss, equivalent to approximately 1 hour of outdoor exposure to bright sunlight at an air temperature of 31°C and a relative humidity of about 75 percent.

The variations of surface temperature of 100-mm (3.937-in.) cubical cement mortar specimens during the wetting and drying cycles are shown in Figure 2. In the drying phase, the specimen surface temperature built up gradually and reached a maximum of about 62°C at the end of the 2-hour period. During the wetting phase, the temperature decreased slightly in the first 15 minutes and then fell fairly quickly to the temperature of water in the next 30 minutes.

A 150-cycle weathering treatment was used in the test program for the purpose of determining if cyclic wetting and drying had any adverse effect on the surface wear resistance of concrete pavement materials. In selection of the number of wetting and drying cycles, the average number of rainy days in a year was used as a guide. An examination of the meteorological data in the last 5 years in Singapore (6) showed that there were, on the average, approximately 150 days with rain each year. Although it may be true to say that a pavement in the field experienced about 150 wetting and drying cycles in a year, it is unlikely that the 150 cycles in the field would be as severe as 150 cycles in the weathering model described

above. This difference is because not all rains would fall during a hot afternoon after pavements had been heated up by sunlight, and not all rains would be followed by intense heating from hot afternoon sun. Compared with the weathering model cycles, most field cycles are likely to have longer drying periods and a more gradual rate of temperature changes.

The accelerated application of wetting and drying cycles in the laboratory was designed to intensify the weathering process. The 150 cycles in the laboratory weathering model would probably achieve a weathering effect equivalent to that produced in the field over a period of 2 years or more. Since the surface deterioration distress described in this paper usually appeared 2 to 3 years after a pavement was open to traffic, the use of 150 laboratory weathering cycles appears to be a reasonable choice for the purpose of this study.

### Surface Wear Resistance Test

A rotating drum test developed by Fwa and Paramasivam (7) for evaluating impact and abrasion resistance of concrete pavement materials was adopted. The test makes use of the Los Angeles machine specified in ASTM Test C535-81 (8). Specimens of 100-mm (3.937-in.) cubes were used, but no abrasive charge was employed. Figure 3 shows a schematic diagram indicating the wearing mechanism in each rotation of the test. Three wearing actions, namely impact, sliding, and rolling, were involved. In each test run, two 100-mm cubes were placed in the drum for 2,000 revolutions. Worn-off materials were removed, and weights of the two cubes were taken at intervals of 200 revolutions. Results of the test are reported in terms of wear, which is computed as follows:

$$W = \frac{m_o - m}{m_o} \times 100$$

where

$W$  = wear in percent by mass,  
 $m_o$  = initial total mass of specimens tested, and  
 $m$  = remaining mass of specimens after wearing treatment.

Studies conducted by Fwa and Paramasivam (7) found the test to have satisfactory repeatability and good sensitivity against variations in the properties of concrete pavement materials tested. Their results indicated that, by conducting three tests for each material type tested, a confidence level of 95 percent can be achieved so that the difference, between sample mean and population mean surface wear, would not exceed an allowable error of 5 percent.

In addition, they observed that the test produced worn specimen surface with good resemblance to a field-deteriorated surface similar to the distress described in this paper. They also found that surface wear of cement mortar test specimens was similar to the initial phase of surface wear of concrete test specimens; they concluded that cement mortar specimens could be effectively used to study the crucial initial phase of surface deterioration, which is of major concern in highway pavement engineering.

### Test Specimen Types

Based on the reasonings of earlier discussions, cement mortar specimens were used in the tests. The cement mortar tested corresponds to that of a concrete with the following mix proportions: cement/sand/coarse aggregate ratio = 1:1.5:2.5 by weight. Test specimens were prepared with the following five water/cement ratios: 0.45, 0.50, 0.55, 0.60, and 0.65.

In all the mixes prepared, an accelerator was added at 1 L per 22 kg (0.27 gal per 50 lb) of cement to give the desired strength at the age of 7 days. The 7-day, 100-mm (3.937-in.) cube strength values of water-cured plain cement mortars, in order of increasing water/cement ratio, were 49.7 N/mm<sup>2</sup> (7,210 psi), 46.0 N/mm<sup>2</sup> (6,670 psi), 41.8 N/mm<sup>2</sup> (6,060 psi), 31.6 N/mm<sup>2</sup> (4,580 psi), and 30.1 N/mm<sup>2</sup> (4,365 psi).

### Test Specimen Exposure Conditions

To evaluate the significance of wetting and drying weathering effects on test materials, three exposure conditions were specified for each material type. Specimens from a batch of mix were divided into three groups, each subjected to a different exposure condition, followed by a rotating drum surface wear test. The three exposure conditions are described below:

1. Initial condition. Cubical test specimens of 100 mm were cast, then demolded after 24 hours, and cured in a water tank for 5 days. The specimens were removed on the 6th day and left in room conditions at approximately 28°C for 1 day. Surface wear test and compressive cube strength test were conducted on the 7th day after casting. The relative humidity varied from about 70 percent in the afternoon to about 95 percent at night.
2. Weathering treatment condition. Test specimens were cast and water-cured as in step 1 above. The specimens were air-dried for 1 day in room conditions at 28°C before they were subjected to alternating wetting and drying in the laboratory weathering tank for 150 cycles. Each weathering cycle consisted of 2 hours of wetting followed by 2 hours of drying. The specimens went through 6 weathering cycles per day, and it took 25 days to complete the 150 cycles. Specimens were again air-dried for 1 day in room conditions after the weathering

condition and before rotating drum surface wear tests were carried out on the 32nd day after casting.

3. Control condition. Test specimens were cast and water-cured as in step 1 above. After removal from a water tank, the specimens were left in room conditions at 28°C for the same duration as the weathering treatment described in step 2 above. Rotating drum surface wear tests were conducted on the 32nd day after casting.

The control condition provides a basis of comparison on which the effect of weathering can be determined from test results of specimens subjected to weathering treatment. Because of the length of treatment duration, some gain in strength took place during this period. The initial condition was therefore included to offer a more thorough examination of changes in surface wear resistance of test specimens.

## ANALYSIS OF TEST RESULTS

The surface wear test data are recorded in Table 1. As an illustration, Figures 4 and 5 show examples of typical progressive wear plots obtained from the surface wear tests. Each curve in the figures represents the average surface wear obtained from three rotating drum tests. Figure 6 summarizes the final results of the test program. Discussed below are findings derived from analyses of the test results.

### Initial Versus Control Conditions

Specimens that underwent the control conditions were tested at an age 25 days older than those tested after the initial water-curing. Table 2 records the strength comparison of specimens tested under these two conditions. All five mixes studied had about a 10 percent increase each in their compressive strength.

The surface wear test results in Table 1 show corresponding increases in surface wear resistance of all materials from initial to control condition. The increase in wear resistance of each mix type was found to be statistically significant at a confidence level of 99 percent. As can be computed from the data in Table 1, each material type had approximately 20 percent less in surface wear. This positive correlation of surface wear resistance with strength is in agreement with the findings of other researchers (9, 10) who studied the resistance of concrete against various forms of abrasion.

### Control Conditions Versus Weathering Treatment

Since specimens that were exposed to control conditions and those exposed to weathering treatment were cast from the same batch of mix and tested at the same age for surface wear, a comparison of their wear test results offers an indication of the significance of the weathering effect on surface wear resistance of test materials.

An examination of the plots in Figures 4–6 reveals that, compared to specimens in control conditions, specimens exposed to laboratory cyclic wetting and drying treatment suffered increased surface wear. Individual statistical tests conducted separately for each of the five mixes concluded that, at 99 percent confidence level, the effect of weathering

TABLE 1 SUMMARY OF SURFACE WEAR TEST RESULTS

Treatment to Specimen	Water/Cement Ratio				
	0.45	0.50	0.55	0.60	0.65
Initial Condition	56.4	60.9	64.9	71.0	76.2
	54.1	58.2	64.0	67.8	78.1
	52.1	64.3	64.4	69.9	78.8
	(54.2%)	(61.1%)	(64.4%)	(69.6%)	(77.7%)
Control Condition	44.3	48.5	53.2	58.4	62.1
	47.6	47.9	51.3	54.0	61.9
	46.4	44.3	51.6	54.4	57.4
	(46.1%)	(46.9%)	(52.0%)	(55.6%)	(60.5%)
Weathering Condition	54.6	58.8	63.9	70.9	73.6
	58.2	63.4	66.5	73.3	76.0
	53.8	57.6	66.6	72.8	74.8
	(55.5%)	(59.9%)	(65.7%)	(72.3%)	(74.8%)

Notes: 1. Values in table represent percentage wear by mass after 2000 revolutions in rotating drum test.  
 2. Each value in parentheses represents average result of 3 rotating drum tests.

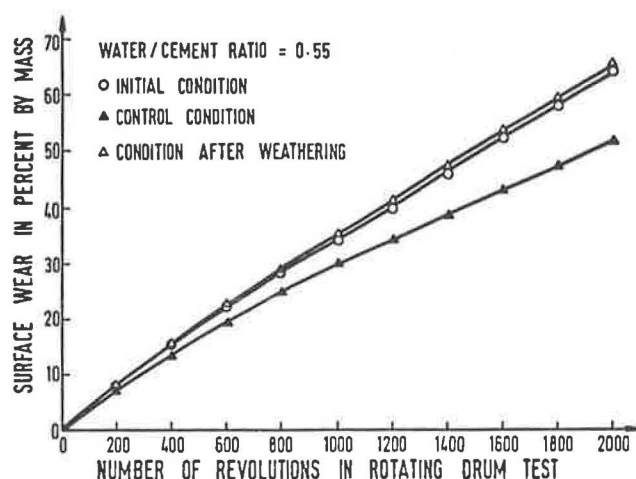


FIGURE 4 Results of surface wear test on cement mortar specimens with water-cement ratio of 0.55.

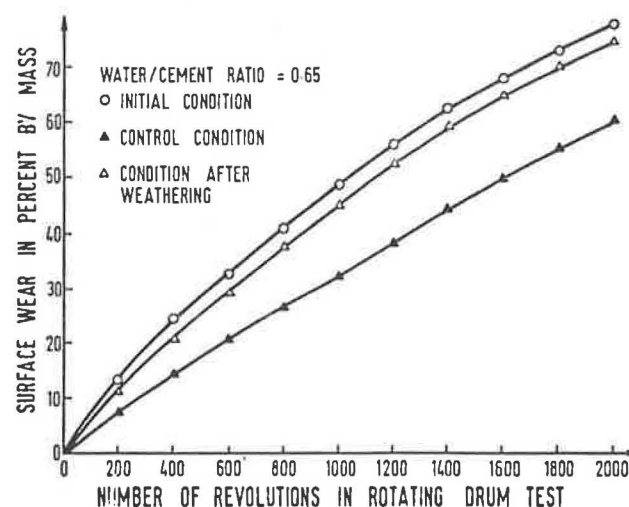


FIGURE 5 Results of surface wear test on cement mortar specimens with water-cement ratio of 0.65.

treatment was significant in reducing the surface wear resistance of test materials.

#### Initial Conditions Versus Weathering Treatment

It is of practical interest to compare the wear resistance of a concrete pavement at the initial stage and at a later phase of its service life after exposure to weathering. On one hand, there will be improvement in wear resistance because of an increase in concrete strength with age; on the other hand, environmental weathering causes deterioration of concrete and reduces its wear resistance. For materials to be used for highway pavement construction, it is highly desirable that its gain in wear resistance with age should at least be sufficient to offset any loss caused by weathering.

For the mixes tested in this study, Figure 6 shows that the gains in wear resistance of test specimens brought about by the growth of mortar strength were more or less offset by the reductions of wear resistance caused by weathering. Although these findings cannot be indiscriminately extended to cover other concrete or cement mortar mixes before similar tests are conducted, it appears logical to state that designers must not simply assume in their designs any increase in wear resistance with age for concrete pavements exposed to weathering.

#### Effects of Water/Cement Ratio

Past studies (7, 9, 10) have found that the abrasion resistance of concrete or cement mortar of a given mix can be improved by reducing its water/cement ratio. In the present study, for



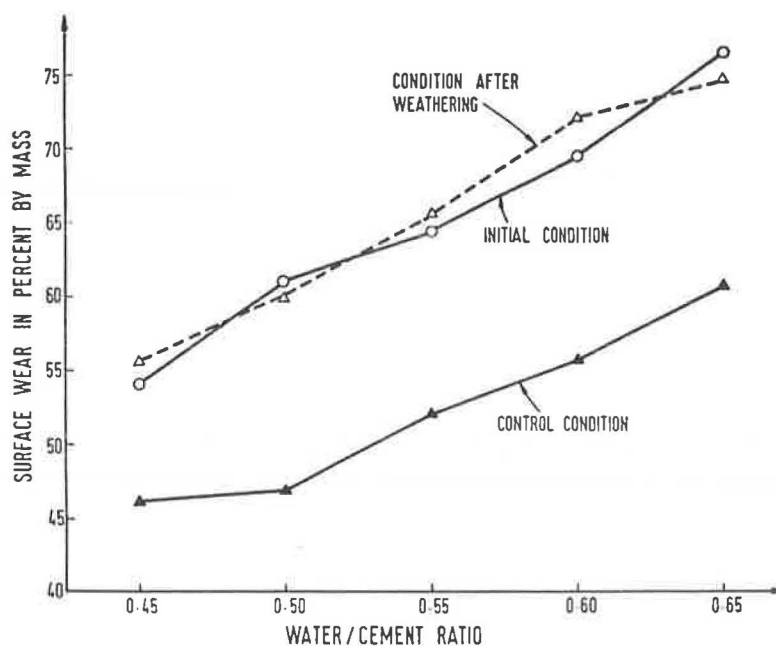


FIGURE 6 Surface wear comparison of test specimens subjected to various exposure conditions.

TABLE 2 COMPRESSIVE STRENGTH OF 100-MM CUBICAL SPECIMENS

Water/Cement Ratio	Cube Strength		
	Initial Condition	Control Condition	Weathering Condition
0.45	49.7 N/mm <sup>2</sup> (7,210 psi)	54.2 N/mm <sup>2</sup> (7,860 psi)	52.1 N/mm <sup>2</sup> (7,555 psi)
0.50	46.0 N/mm <sup>2</sup> (6,670 psi)	49.4 N/mm <sup>2</sup> (7,165 psi)	51.0 N/mm <sup>2</sup> (7,395 psi)
0.55	39.3 N/mm <sup>2</sup> (5,700 psi)	44.7 N/mm <sup>2</sup> (6,480 psi)	42.1 N/mm <sup>2</sup> (6,105 psi)
0.60	31.6 N/mm <sup>2</sup> (4,580 psi)	36.2 N/mm <sup>2</sup> (5,250 psi)	34.3 N/mm <sup>2</sup> (4,975 psi)
0.65	30.1 N/mm <sup>2</sup> (4,365 psi)	35.4 N/mm <sup>2</sup> (5,135 psi)	33.8 N/mm <sup>2</sup> (4,900 psi)

those specimens that were water-cured as in the "initial condition" case, and those that were water- and subsequently air-cured as in the "control condition" case, one would expect the relationship between surface wear and water/cement ratio to hold. It would be interesting to find out if the same is also true for test specimens subjected to weathering.

Referring again to Figure 6, we see that although the initial and control test data demonstrated the trend anticipated, surface wear data of the "condition-after-weathering" case also produced better wear resistance when the water/cement ratio of the mix was reduced. The shapes of the curves of the wear vs. the water/cement ratios for the three test conditions are

similar. Based on these test data, it appears appropriate to say that lowering the water/cement ratio can be an effective means of improving the wear resistance of concrete pavements exposed to climatic weathering.

#### Relationship Between Wear Resistance and Compressive Strength

For a given mix of concrete material, it is convenient to think that its surface wear resistance would improve as its compressive strength increases. Fwa and Paramasivam (7) have

shown, however, that such a relationship is likely to be non-linear in nature, and it varies among various mixes of cement mortar. One must therefore refrain from using concrete or mortar compressive strength as a relative indicator of the wear resistance of various concrete materials. The test results in this study provide further confirmation of this view.

In Figure 7 the surface wear of test specimens exposed to various conditions are plotted against their compressive strength. Looking at the test results of each of the three treatment conditions independently, one can conclude that among specimens there existed a trend of decreasing surface wear with increasing compressive strength. The same however cannot be said when one combines the test data of specimens treated under different exposure conditions. At any compressive strength level, it can be seen that surface wear values could differ by as much as 15 percentage points. There was clearly no unique relationship between compressive strength and surface wear in this case.

It is interesting to note that the compressive cube strength of specimens exposed to weathering and that of specimens under control conditions were similar. There was, however, a large difference in their respective surface wear resistance. It is possible that although the weathering treatment had caused deterioration of the surface layer of test specimens, as reflected by the increased surface wear in these specimens, it was not intensive enough to have adverse effects on the interior of the specimens and their overall compressive strength.

## CONCLUSIONS

Based on the findings of the test program, the following conclusions may be drawn:

1. As the strength of concrete increased with age, the lim-

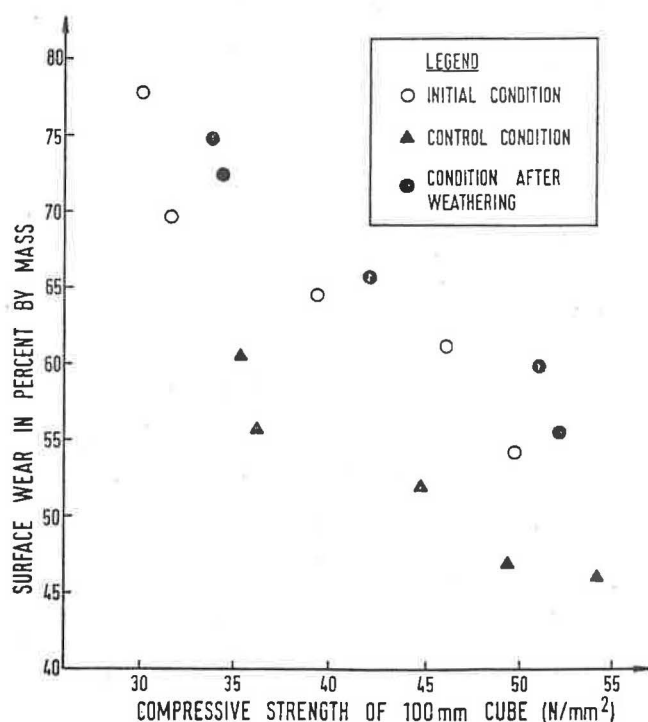


FIGURE 7 Relationship between compressive strength and surface wear resistance of test specimens.

ited test results in this study suggest that there was a corresponding gain in wear resistance as cement mortar matured.

2. The laboratory-accelerated wetting and drying weathering treatment caused statistically significant reductions in surface wear resistance of all cement mortar mixes tested. The test was found useful in providing an indication of the detrimental effects that adverse weather conditions have on the wear resistance of concrete pavements.

3. For a highway concrete pavement that is exposed to weathering in its service life, one must not assume that its wear resistance would improve with time as the concrete ages. The present study showed that the reduction in wear resistance caused by weathering could be higher than the gain brought about by maturation of cement mortar.

4. Test results showed that an improvement in wear resistance of the test specimens under weathering conditions could be effected by lowering the water/cement ratio of the cement mortar mix.

5. The wear resistance of a concrete pavement is essentially a function of its surface properties. It cannot be uniquely related to its compressive strength measured from conventional cube tests.

6. Although no correlation can be made at this stage with field performance of in-service pavements, the test results obtained in this study indicate that the test procedure adopted could be useful in evaluating the relative surface wear resistance and durability of various concrete pavement materials.

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