Freeze-thaw durability tests upon concrete paving block specimens

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Introduction

CONCRETE block paving, in common with any other paving, must be of a quality sufficient to ensure an adequate resistance to damage by both vehicles and weather during the design life of the pavement. Surface and structural damage to pavements caused by alternate freezing and thawing can be a serious problem in many countries. This damage is exacerbated by the use of de-icing salts. Fortunately, in concrete pavements an excellent resistance to such damage is effected by incorporating the correct proportion of air in a properly proportioned and manufactured concrete. In the UK, if it is to be considered adequately durable, a paving quality concrete must be air-entrained and contain 3 to 6% by volume of air; it must also have a minimum indirect tensile strength of 1.8 N/mm^2 at 28 days, a minimum cement content of 280 kg/m^3 and a maximum water/cement ratio of 0.55[1].

The manufacturing process used to produce paving blocks requires that the concrete used shall be of a low moisture content. The stiff consistence of the fresh concrete inhibits the action of air-entraining agents and, also, makes the measurement of the air content extremely difficult, therefore, air-entrainment is not used in concrete paving blocks. To ensure adequate durability under the combined action of frost and de-icing salts, it has been the practice in Europe to specify a level of paving block strength. This strength was derived from experience gained over many years of the performance of block paving when exposed to natural freeze-thaw cycles plus de-icing salts.

Five years ago, the Cement and Concrete Association, when producing a specification for concrete paving blocks, followed this precedent, basing the level of strength specified upon European experience and upon some freeze-thaw tests carried out in the laboratory[2]. Recently, more extensive tests have been carried out to evaluate this practice and to obtain a better understanding of the factors affecting the resistance of concrete paving blocks to damage by frost and de-icing salts.

It was originally intended that the specimens for the tests should be manufactured in the laboratory using a series of mixes that covered the aggregate types and mix proportions used in the production of the paving blocks. However, following discussions with paving block manufacturers and representatives of the County Surveyors' Society, it was decided that the specimens would be more representative if they were produced on a standard production machine. A number of companies offered their services for this purpose and the specimens were eventually made by S Marshall & Sons Limited, using Sutcliffe Speakman plant.

TABLE 1: Mix details – Phases I and II

Specimen code	*Aggregate*	*Cement content (kg/m³)*	*Moisture content (%)*	*Aggregate: cement ratio*	*Water/cement ratio*
PHASE I					
1/R+G/5.2	$R_1 + G_1$	570	5.2	3 : 1	0.22
1/R+G/6.9	$R_1 + G_1$	570	6.9	3 : 1	0.30
2/R+G/5.0	$R_1 + G_1$	456	5.0	4 : 1	0.26
2/R+G/6.8	$R_1 + G_1$	456	6.8	4 : 1	0.36
3/R+G/5.2	$R_1 + G_1$	380	5.2	5 : 1	0.33
3/R+G/7.0	$R_1 + G_1$	380	7.0	5 : 1	0.45
1/G+G/6.2	$G_2 + G_3$	570	6.2	3 : 1	0.27
a1/G+G/6.1	$G_2 + G_1$	570	6.1	3 : 1	0.25
a1/G+G/7.1	$G_2 + G_3$	570	7.1	3 : 1	0.30
2/G+G/6.0	$G_2 + G_3$	456	6.0	4 : 1	0.32
b2/G+G/5.9	$G_2 + G_1$	456	5.9	4 : 1	0.31
PS	$R_1 + L + G_2$	estimated as 350		5.8 : 1	
1/R+R/5.4	R_1	570	5.4	3 : 1	0.23
1/R+R/6.9	R_1	570	6.9	3 : 1	0.30
2/R+R/5.5	R_1	456	5.5	4 : 1	0.29
2/R+R/6.9	R_1	456	6.9	4 : 1	0.37
3/R+R/6.5	R_1	380	6.5	5 : 1	0.41
3/R+R/6.9	R_1	380	6.9	5 : 1	0.44
PHASE II					
A	$R_1 + L + G_1$	474	6.8	3.7 : 1	0.32
B	$R_1 + L + G_1$	267	4.2	7.6 : 1	0.36
D	$R_1 + L + G_1$	183	4.9	11.5 : 1	0.62

R_1 — Mount Sorrel Granite (10 mm maximum size)
G_1 — North Notts Sand
G_2 — Gravel (Sandy, Bedfordshire) (5 mm maximum size)
G_3 — Sand (Sandy, Bedfordshire)
L — Limestone (5 mm maximum size)

Test details

The test programme was carried out in two phases and Table 1 gives the mix details of all the specimens tested. All paving block specimens were 200 x 100 x 65 mm thick, these being the same dimensions as one of the range of paving blocks produced by S Marshall & Sons Limited. In Phase I, aggregate types and mix proportions were selected, as previously described, to cover the ranges used by all manufacturers. It was found, however, that the manufacturing process used to form the specimens (which was by the application of pressure alone unlike some other processes in which vibration is the

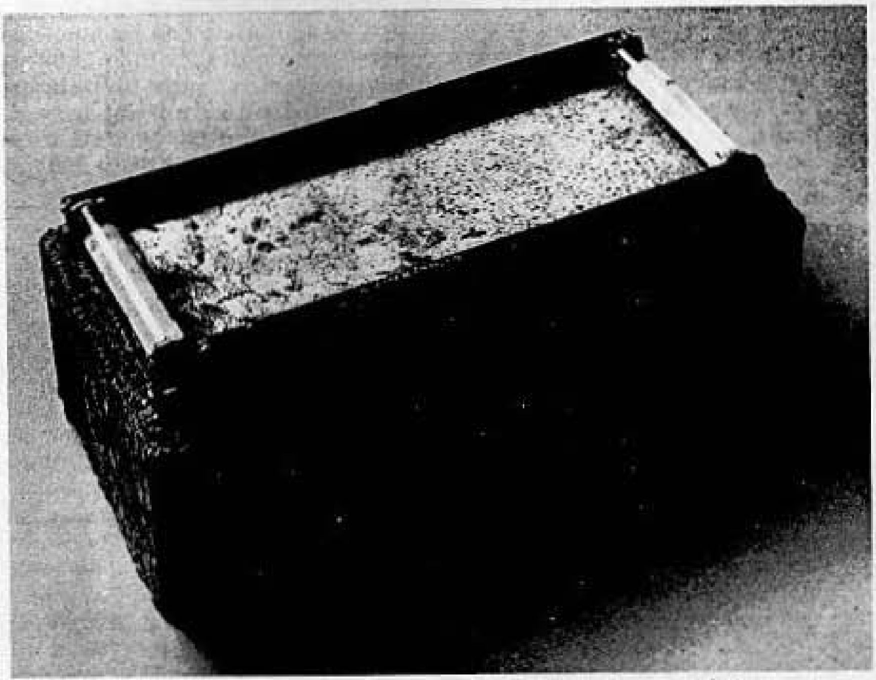


Figure 1: Specimen ready for testing but prior to application of de-icing solution.

main means of compaction) had difficulty in producing the gravel and natural sand (G + G) specimens especially with the lowest cement content. An attempt to overcome this difficulty was made by changing to a finer sand from a different source but this failed significantly to improve the situation and therefore no gravel specimens were produced with the lowest cement content.

The Phase I tests also included 200 x 100 mm specimens cut from paving slabs made to BS 368:1971[3]; these specimens were of a similar thickness to the other test specimens. There are very few, if any, reported instances of paving slabs made to BS 368 suffering from frost plus de-icing salts and it was intended that these specimens should be used both as a basis upon which to judge the severity of the test regime and as a datum with which the performance of block specimens could be compared.

Phase II tests were on specimens with a lower cement content and

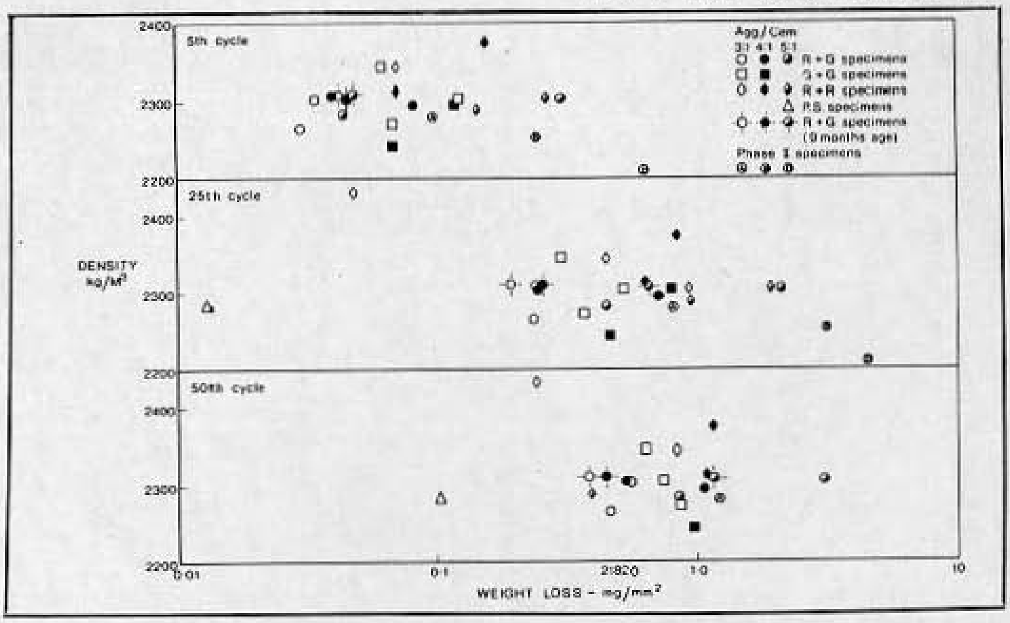


Figure 2: Relationship between density (average of 5 specimens) and weight loss

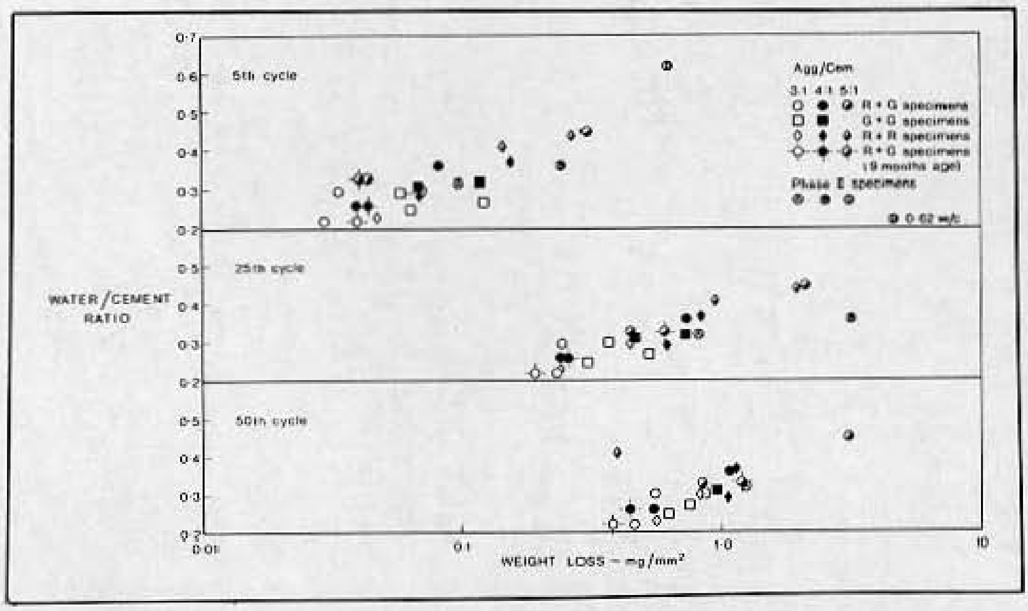


Figure 3: Relationship between water/cement ratio and weight loss

TABLE 2: Surface damage rating

Rating	
0	No scaling
1	Very slight scaling (1 mm depth, no coarse aggregate visible)
2	Slight to moderate scaling
3	Moderate scaling (some coarse aggregate visible)
4	Moderate to severe scaling
5	Severe scaling (coarse aggregate visible over entire surface)

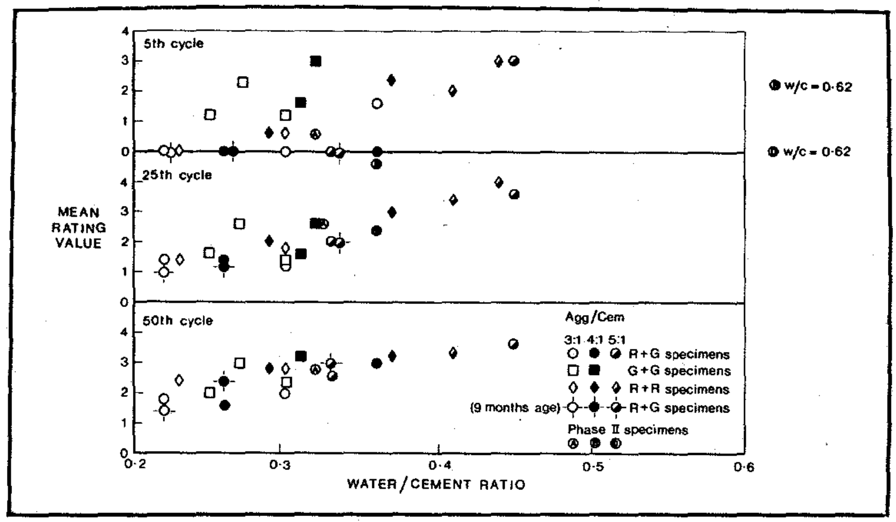


Figure 4: Relationship between mean value rating and water/cement ratio

specimens of a greater age than those tested previously. Normally, specimens were first exposed to the freeze-thaw regime at an age of approximately 35 days; in Phase II, however, some unused specimens from Phase I were tested to determine what effect, if any, age had upon their durability. The specimens with lower cement contents were tested to obtain further information upon the effect of cement content on durability.

Freeze-thaw regime

The paving block specimens were subjected to a freeze-thaw regime that complied with the RILEM Recommendation CDC 2[4]. This recommendation requires that the specimens should be subjected to a temperature of -20°C ±2°C for a period of 16 to 17 hours before thawing for 7 to 8 hours. The capacity of the freezer used for the tests must be such that the air temperature at 100 mm distant from any specimen shall be -18°C or cooler at 7 hours freezing.

The specimens are exposed to de-icing solutions by forming a dam on the surface of the specimen (see Figure 1) within which a 2-3 mm deep, 3% concentration of de-icing solution (weight/volume in water) can be contained. A 3% solution is recommended because this has been shown to be a critical concentration in frost attack upon concrete. Rock salt, most commonly used in the United Kingdom in de-icing public roads, was used to make up the solution used in these tests.

To assess the durability of the specimens, the RILEM method recommends that at regular intervals throughout the test measurements shall be made of the weight of spalled material, if any, and observations made of the severity of the spalling, i.e. depth, area and rating of the surface damage caused. The levels of assessment used in the rating of surface damage are shown in Table 2. It should be noted that, for the specimens tested, the maximum size of aggregate used was 10 mm. In this test programme, assessments of the damage, if any, were made at the end of every fifth cycle to a maximum of 50 cycles unless the specimen was withdrawn through failure. Failure was defined, for this purpose, as the point at which the brine solution could not be retained by the dam due to excessive loss of surface material from the specimen.

Simultaneously with the exposure of specimens for the first time to the freeze-thaw regime, a number of tests was also carried out upon other specimens taken from the same batches. These tests were compressive strength (as per the Cement and Concrete Association specification[5]), absorption, dry density and initial surface absorption. It was hoped that the results from these tests, together with those obtained from the freeze-thaw tests, would identify parameters that could be used in the prediction of the durability of a paving block exposed to frost plus de-icing salts.

Results

The relationship between the results obtained in the various tests carried out on the paving block specimens remained largely unchanged throughout the freeze-thaw tests. This is demonstrated in Figures 2, 3 and 4 at 5, 25 and 50 cycles. To help reduce the number of Figures, where the result pattern does not permit more than one set of results in a Figure, only those obtained at 25 cycles are given.

The cumulative average weight losses recorded at intervals of 5 cycles for the specimens tested in Phases I and II are shown in Figures 5 to 8. Five specimens were tested for each mix; where specimens failed to complete the full test programme, this is indicated in these Figures. A particular example of this is in Figure 7 where two 3/R + R/6.5 specimens had to be withdrawn at 25 cycles and therefore the weight loss values from 30 cycles onwards are the average of three specimens only.

Generally, for a given water/cement ratio, the rate of weight loss was the same irrespective of the particular aggregate combination used in manufacture. Some of the results obtained for the gravel and natural sand specimens (G + G) were influenced by failure of one or two pieces of the gravel aggregate in the freeze-thaw cycles. It has already been reported that, due to the method of manufacture, some difficulty was experienced in producing these specimens. This led to a rather exposed surface finish which probably contributed to the attack upon some of the aggregate.

The first instances of spalling usually occurred where a larger piece of aggregate lay immediately below the surface. Depending upon the specimen, this spalling then tended to spread and, in extreme cases, led to loss of the larger aggregate. Although in some cases surface loss could not be detected visually, all block specimens suffered some degree of surface loss by the completion of five freeze-thaw cycles. The paving slab specimens, however, did not suffer any loss until the 25th cycle, when one of the specimens became slightly spalled. This was joined at 35 cycles by a second specimen but the remaining three specimens were unaffected by the freeze-thaw regime. This would appear to indicate that the laboratory tests were no more severe than natural conditions. However, it is possible that the durability of the paving slab in relation to frost and de-icing salts is greater than is required for the natural conditions experienced in service and, therefore, the regime could be more severe than natural conditions.

Results obtained from the tests carried out in parallel with the freeze-thaw tests are shown in Figures 2, 9, 10 and 11 plotted against the average cumulative weight loss values recorded for the freeze-thaw specimens. Despite the range of cement contents used in the Phase I tests, 380-570 kg/m³, the range of block strengths obtained remained fairly narrow and no positive relationship was established between the strength of the specimens and their weight loss. In an attempt to widen the range of block strengths, Phase II tests included specimens of a lower cement content than the lowest used in Phase I. The results obtained from these specimens (B and D) did fit the relationship that had been presumed

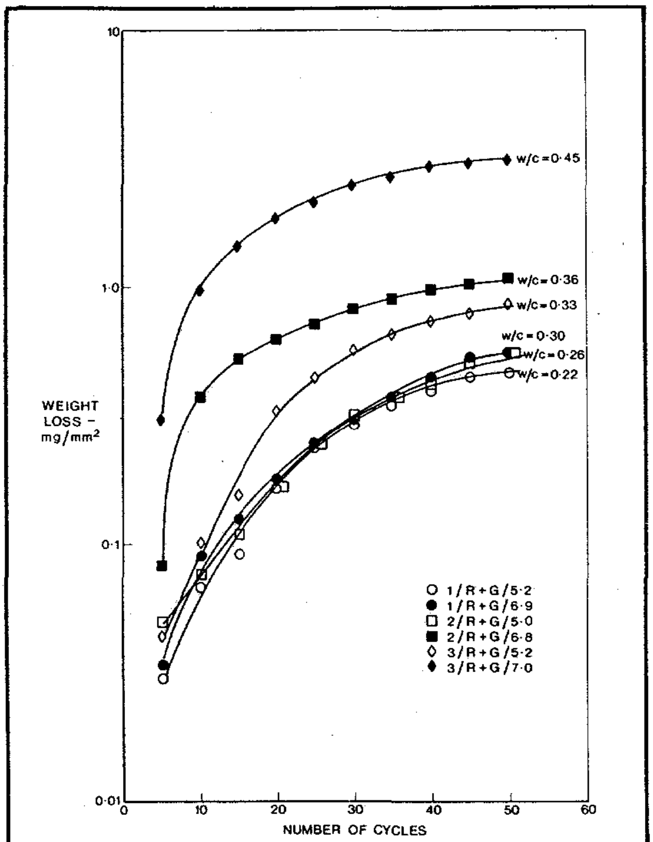


Figure 5: Relationship between average cumulative weight loss (5 specimens) and number of freeze-thaw cycles

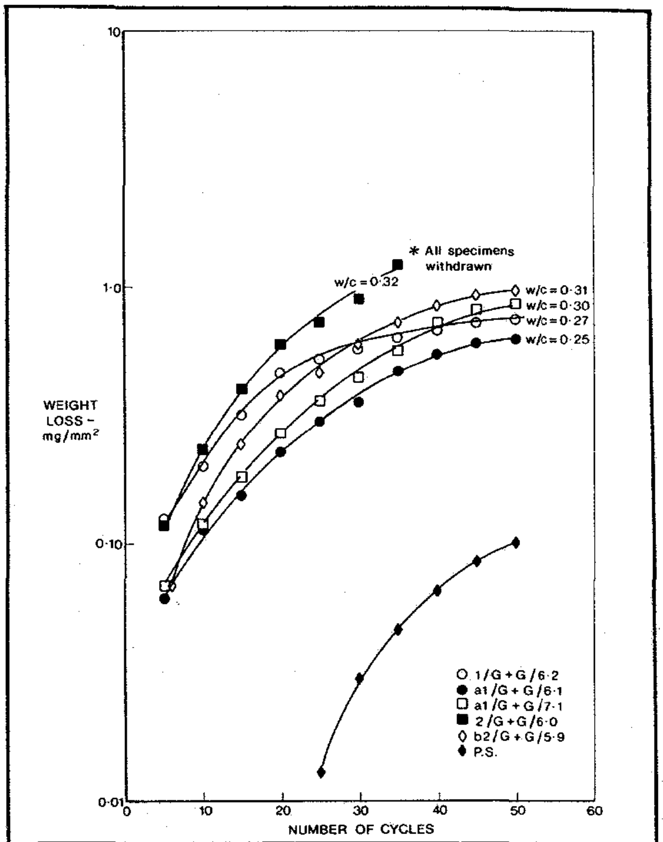


Figure 6: Relationship between average cumulative weight loss (5 specimens) and number of freeze-thaw cycles

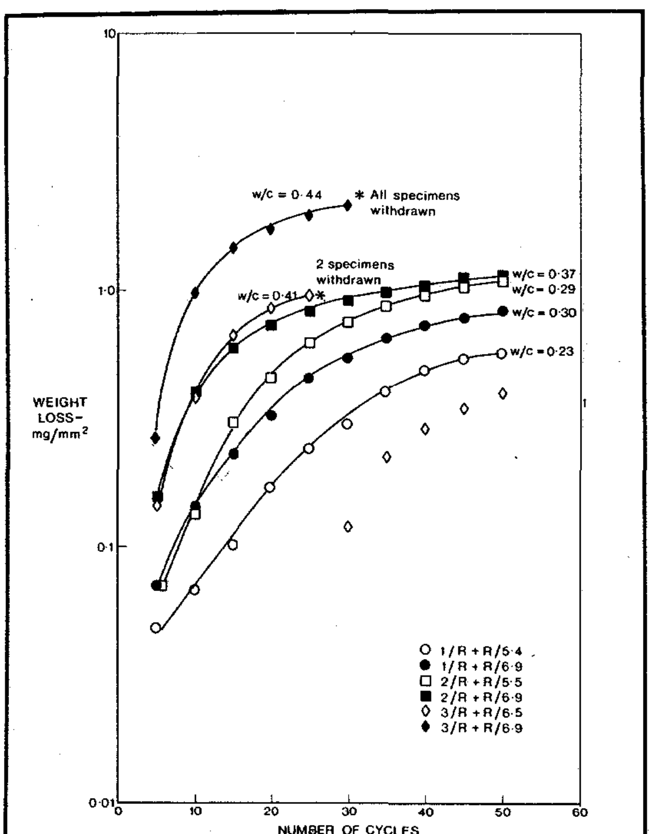


Figure 7: Relationship between average cumulative weight loss (5 specimens) and number of freeze-thaw cycles

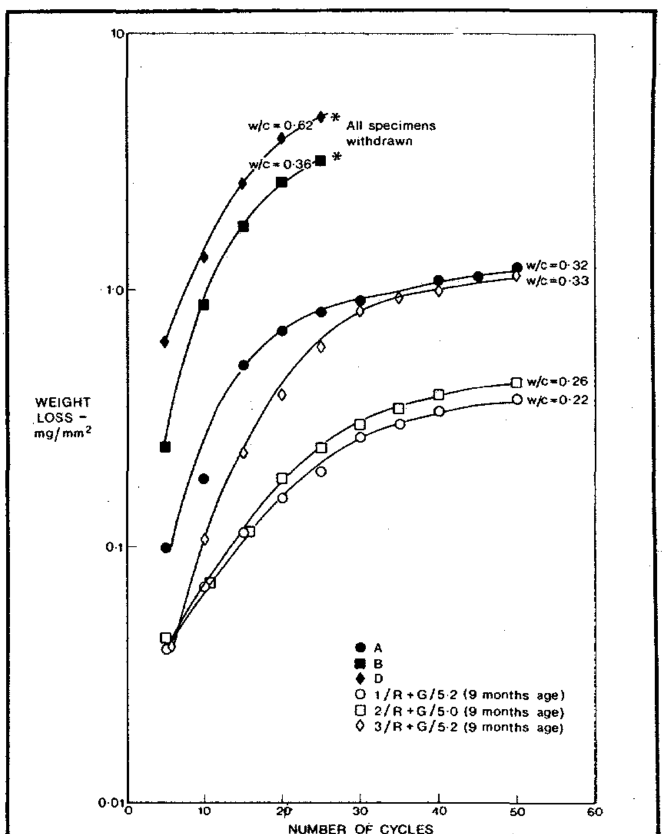


Figure 8: Relationship between average cumulative weight loss and number of freeze-thaw cycles

at the start of the programme but, overall, the correlation between strength and weight loss could not be said to have been proved.

Phase II tests upon nine-month old block specimens showed that although age had led to a significant increase in strength (19-45%) the weight losses remained approximately the same as those obtained for specimens tested in Phase I. Only three mixes were tested in this way and further tests would be necessary in order to fully investigate this result. The rather large gain in strength between 35 days and 9 months is judged to be caused by the initially low level of hydration, due to the low moisture content of the concrete mix, being increased by moisture in the atmosphere surrounding the specimens until the time of testing at 9 months.

Like compressive strength, the

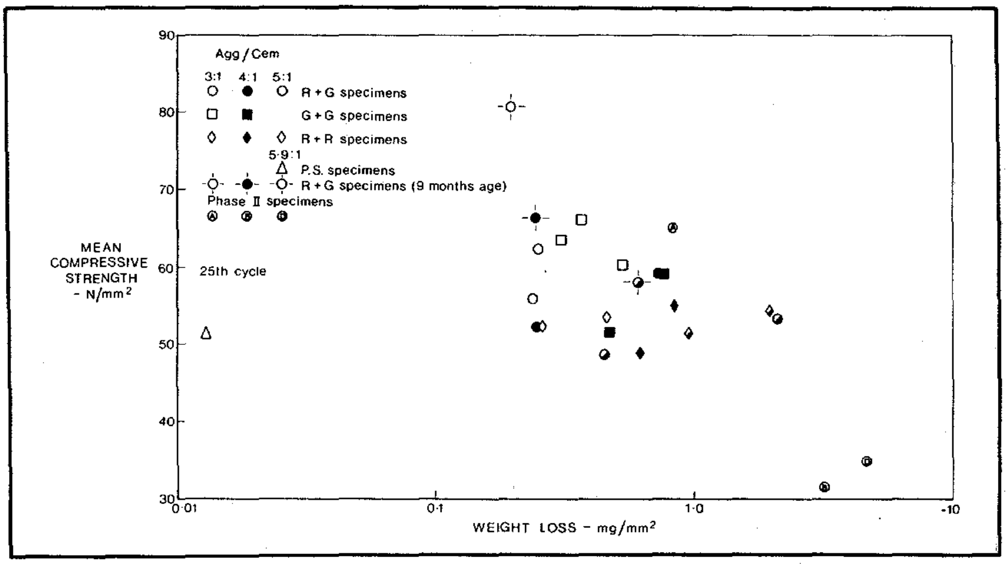


Figure 9: Relationship between mean compressive strength (10 specimens) and weight loss

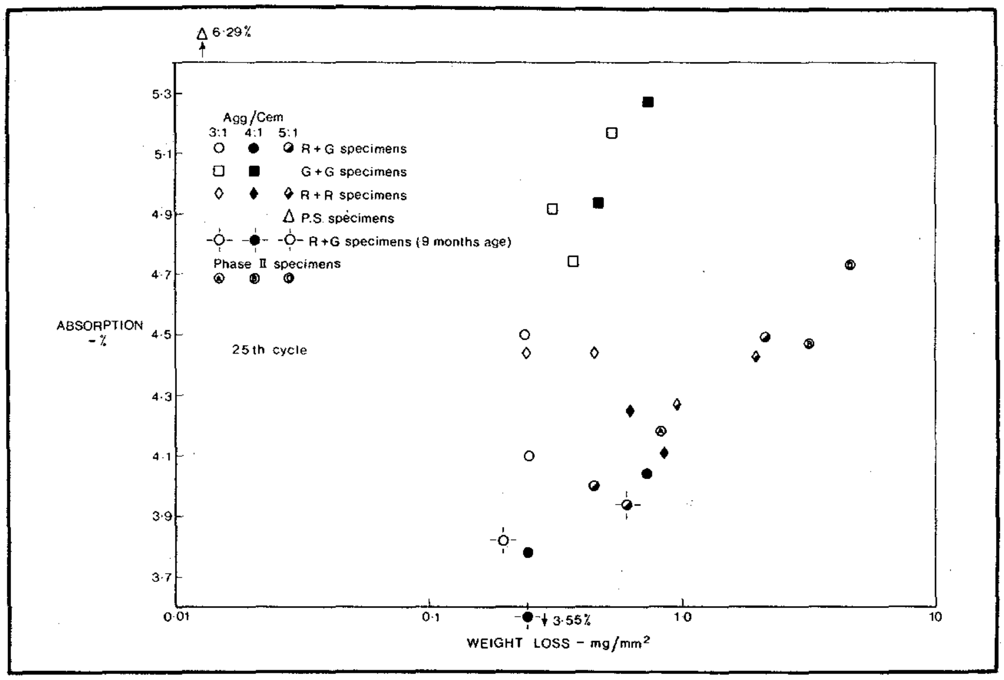


Figure 10: Relationship between absorption at 24 hours (average of 5 specimens) and weight loss

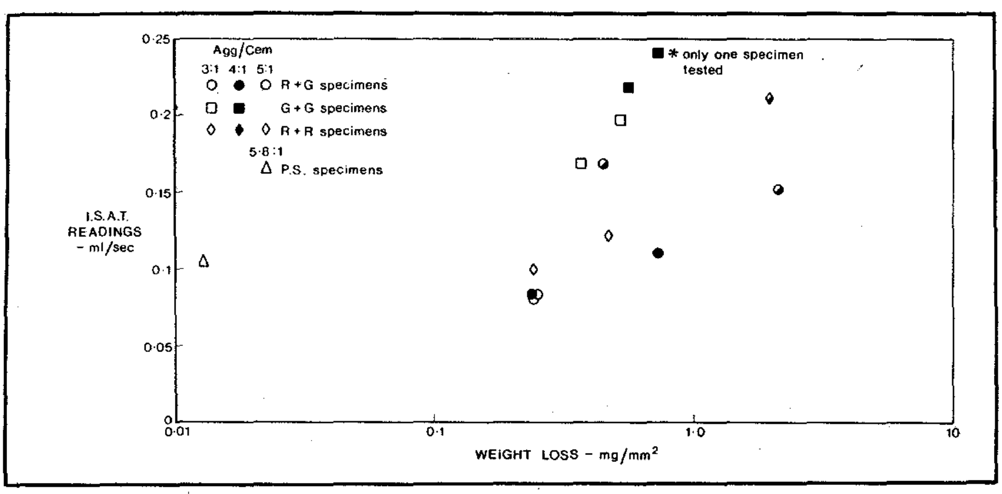


Figure 11: Relationship between ISAT at 10 minutes (average of 3 specimens) and weight loss at 25 cycles

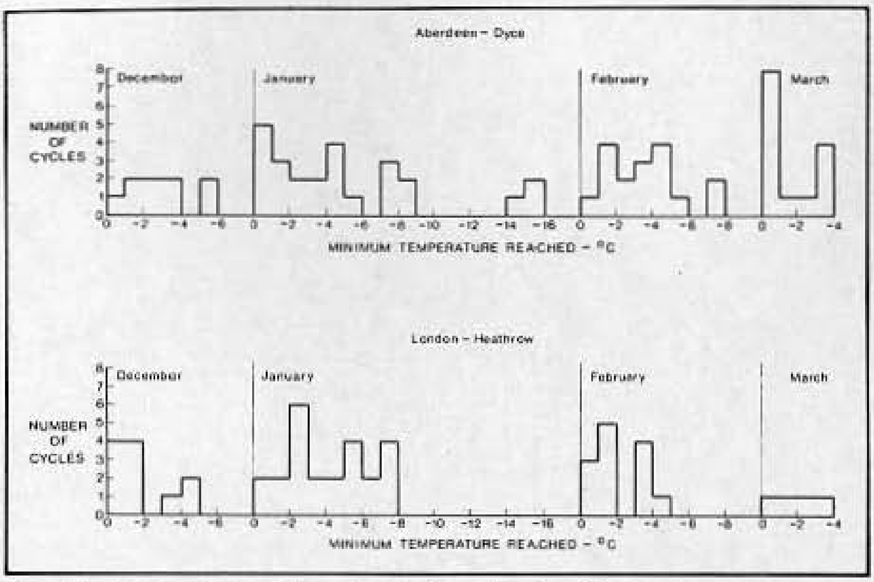


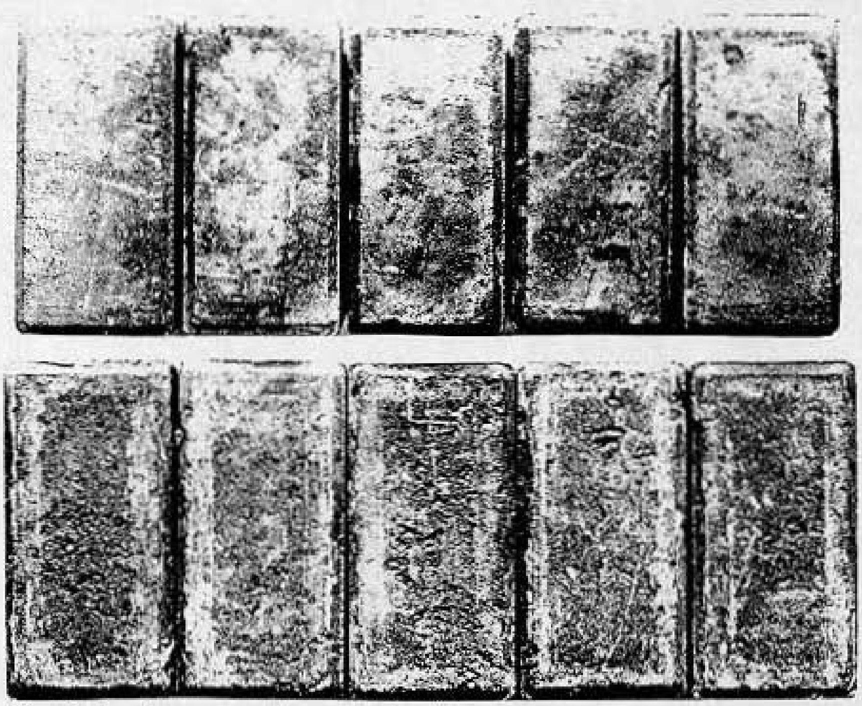
Figure 12: Number of natural freeze-thaw cycles at Aberdeen (Dyce) and London (Heathrow) – 1978/79

absorption, density and initial surface absorption (ISAT) also failed to exhibit a positive correlation with weight loss, see Figures 2, 10 and 11. Although, due to difficulties with the apparatus, not all ISAT results were obtained in Phase I and none at all in Phase II, it is thought that, even if all results had been gathered, a more positive relationship would not have been obtained. The lack of any definite relationship between weight loss and absorption, density or surface absorption would appear to indicate that these tests could not be used successfully to predict the durability of paving blocks.

Water/cement ratios (see Table 1) were derived from "Speedy" moisture measurements taken on the mixes used in the production of the specimens. These ratios are shown in Figure 3 to have a direct correlation with the weight loss of the freeze-thaw specimens. This relationship is also demonstrated in Figures 5 to 8. Cement content is intrinsically linked with water/cement ratio; Figure 3 also shows that improved durability in the tests was generally provided by an increase in the cement content.

The paving slab specimens completed the freeze-thaw tests comparatively undamaged even though their cement content was the lowest of the Phase I specimens. It is thought that the durability of these specimens is produced by the method of manufacture. In this process, the concrete mix supplied for the paving slabs is of high water content. Once placed in the mould, pressure is applied to the concrete by an hydraulic ram and a large proportion of the water in the mix is squeezed out. At the completion of the pressing operation, the slab is ejected from the mould having attained sufficient strength to be mechanically handled. The passage of the water through the concrete during the production process carries fine material with it. Loss of this material is prevented by filter papers on both faces of the slab, which produce a concentration of the finest particles – cement – on the surfaces of the slab. These surfaces, therefore, have a high cement content and, because the water content has been considerably reduced, a low water/cement ratio, factors which the tests have shown produce a higher freeze-thaw durability.

As was to be expected, surface damage ratings produced a similar correlation with water/cement ratios and cement contents (see Table 2). The Phase II low cement content specimens suffered a significantly higher weight loss than other specimens; however, as the Phase I specimens with a cement content of 380 kg/m^3 had generally suffered the higher weight losses in the first series of tests, this increase in damage was to be expected with a still further reduction in cement content.



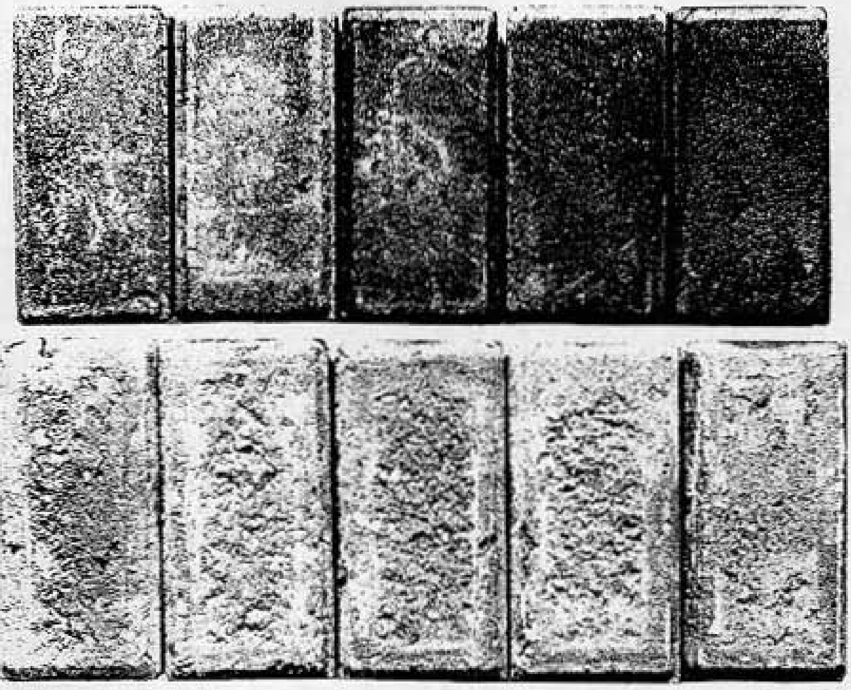
Max depth:	1	1	2	1	1	mm
Area:	50	3	7	4	4	%
Rating:	2	1	2	2	2	

Figure 13: Specimens 1/R + G/5.2 before start of test (above) and after 50 freeze-thaw cycles

Discussion of results

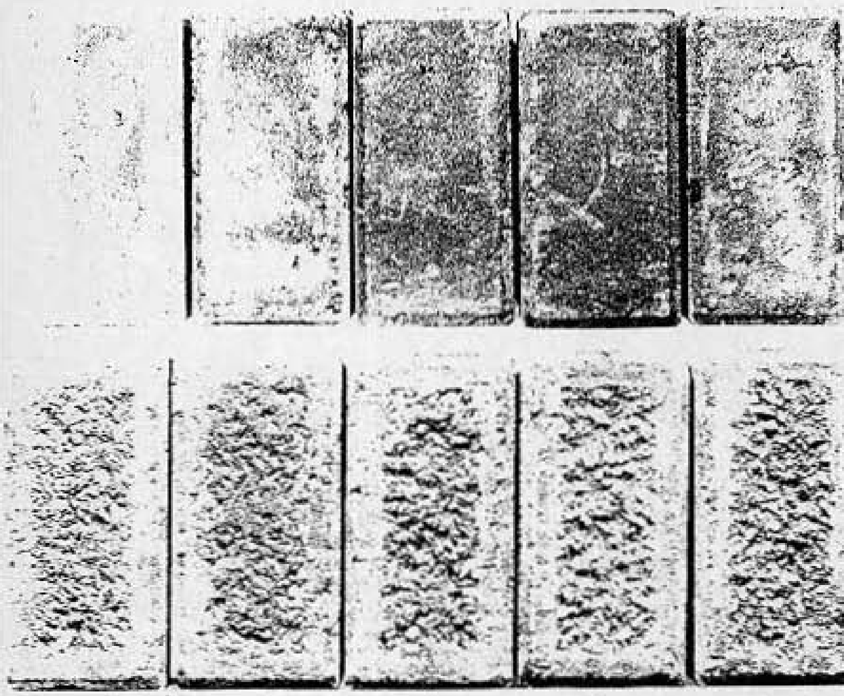
The freeze-thaw regime used in these tests attempts to simulate the conditions that can occur in a natural situation. Figure 12, which shows the number of freeze-thaw cycles experienced in the winter of 1978-79 at two locations in the United Kingdom, indicates that the number of test cycles was reasonable. The severity of the tests has also been discussed previously in connection with the performance of the paving slab specimens. Although it is possible that paving slabs complying with BS 368 are of greater durability than is required for the conditions to which they are exposed in service, the minimal level of damage caused to the slab specimens suggests that, even if this were correct, the test regime was only slightly more severe than natural conditions. The results obtained from the tests can therefore make a useful contribution towards specifying the freeze-thaw durability of concrete paving blocks.

From the data obtained and bearing in mind the scope of this investigation, the results of the tests did not show a very clear correlation between compressive strength and



Max. depth:	2	2	1	2	1	mm
Area:	40	75	90	90	20	%
Rating:	3	3	3	4	2	

Figure 14: Specimens 2/R + G/6.8 before start of test (above) and after 50 freeze-thaw cycles



Max. depth:	2	2	2	2	2	mm
Area:	100	100	100	100	100	%
Rating:	3	3	4	4	4	

Figure 15: Specimens 3/R + G/7.0 before start of test (above) and after 50 freeze-thaw cycles

weight loss; therefore, it would appear that, by itself, strength is not an ideal means of predicting durability. However, most specifiers will prefer to have a simple test that can be used to assess compliance. Absorption, density and initial surface absorption all exhibited an even lower correlation than strength with weight loss. If a simple test is to be included, it would appear that compressive strength is the best choice from the various parameters that have been examined. From the data obtained in the tests is is suggested that a minimum mean block strength of 50 N/mm² could be used in a compliance test. This strength level is based upon values obtained at 35 days for ten specimens tested in accordance with the Cement and Concrete Association specification[5].

From the correlation obtained between water/cement ratio, cement content and weight loss, it is apparent that water/cement ratio or cement content can be used to ensure a reasonable durability. Although water/cement ratio produced the most positive effect upon weight loss, this is a factor that would be extremely difficult to check, should the specifier wish to do so. Therefore, as the range of moisture contents used in the manufacture of paving blocks is fairly narrow and largely set by the production process, it would appear that setting a minimum cement content is a suitable method of ensuring durability. Specimens of cement contents below 380 kg/m³ suffered considerable surface damage and, even at 380 kg/m³, some specimens still suffered quite severe surface damage. It would appear, therefore, that 380 kg/m³ is the absolute minimum level of cement content that can be permitted and still obtain a reasonable level of durability.

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