Concrete: Construction's Sustainable Option

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Study of the performance of natural gravel of marginal soundness in concrete

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ABSTRACT. A laboratory study was carried out to assess the performance in concrete of a carboniferous limestone gravel that was of marginally soundness in the loose state. In particular, the effects on the concrete soundness of the different mineralogical constituents and the surface porosity and shape distributions of the gravel particles were examined. Twenty-four tablets of ordinary Portland cement concrete were prepared using silica sand and the 14.0 to 20.0-mm gravel fraction. A specific mineralogy, particle shape and relative surface porosity was used in manufacturing the different tablets. The soundness of the tablets was assessed using a methodology similar to that employed in the standard magnesium sulphate soundness (MSS) test. A comparison of the behaviours of the loose and bound gravel particles indicated that the performance of the loose gravel measured using the MSS test was a good indicator of the performance when set in concrete. Overall, the carboniferous limestone, silicified limestone, chert, quartz, quartzite and micro-granite constituents were all sound. The low porosity sandstone particles tended to be of marginal soundness whereas the medium to high porosity sandstone and particularly the siltstone particles were unsound.

Keywords: Gravel, Concrete, Soundness, Magnesium sulphate.

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INTRODUCTION

A laboratory study was carried out to assess the in-service performance of a natural gravel of marginal soundness in the loose state. Soundness is a measure of the resistance to breakdown or disintegration during repeated wetting and drying or freeze-thaw cycles. In particular, the effects of the different mineralogical constituents and the surface porosity and shape distributions of the gravel particles on the soundness of concrete mixes were examined. Specimens of ordinary Portland cement concrete were prepared using silica sand and uniform gravel and the soundness of the hardened concrete mixes was assessed using a similar methodology to that employed in the magnesium sulphate soundness (MSS) test. The MSS test simulates the effects of repeated freeze-thaw cycles (the most severe of the weathering processes) on loose, wet aggregate and the degree of soundness is characterised empirically by a MSS value (equation 1).

$$\text{MSS value} = m_2/m_1 \quad (\text{x } 100) \qquad [1]$$

where m_1 is the initial dry mass of the aggregate specimen and m_2 is its dry mass after five cycles of immersion in the salt solution and oven drying.

The methodology employed in this study was to immerse concrete tablets, which had been manufactured using the gravel, into a supersaturated magnesium sulphate solution rather than the loose gravel alone, as per the standard test method [1]. The validity of the MSS test in assessing the performance of the aggregate in concrete was also assessed by comparing the behaviours of the loose and bound gravel particles. Numerous researchers, including Wu et al. [2], have suggested that there may not necessarily be a strong relationship between the performance of the loose aggregate during the MSS test and its in-service performance. The effects of an exposed aggregate finish to the concrete tablets was also investigated.

MATERIALS AND METHODS

Materials

Ordinary Portland cement, silica sand and a 14.0 to 20.0-mm natural limestone gravel was used in the design mix. The silica sand was chosen because of its inert properties. The pit-gravel was of glacial origin and although predominantly carboniferous limestone, it also comprised numerous other rock types (Table 1). The 14.0 to 20.0-mm size fraction had already been test for soundness in the loose state and had performed only marginally well with MSS value of about 90% [3]. The carboniferous limestone, silicified limestone, chert, quartz, quartzite, and micro-granite constituents were all sound; the low porosity sandstone particles were of marginal soundness whereas the medium to high porosity sandstone and siltstone particles were generally unsound. The gravel as a whole had a water absorption value of 2.4% dry mass and relative density values of 2.51 and 2.56 on oven-dried and saturated-surface-dried basis, respectively.

Table 1 Constituents of the limestone gravel [3].

MINERALOGY	DRY MASS (%)
Carboniferous limestone	58.2
Sandstone (low porosity)	12.0
Sandstone (medium to high porosity)	7.9
Silicified limestone	9.2
Chert	6.3
Siltstone	4.0
Quartz, quartzite and microgranite	2.3

A 50-kg bulk sample of the gravel was washed in distilled water, oven dried at a temperature of 105–110^{o}C and subdivided according to the mineralogy, shape and surface porosity of the constituent particles. Firstly, a megascopic examination was conducted to separate the constituent particles into broad rock categories with further subdivision on the basis of colour and physical condition, namely grain size and relative surface porosity (assessed using a stereoscopic microscope). The different particle shape categories, namely angular, flaky alone, elongate alone, and both flaky and elongate, were then separated out. Each subdivision comprising a specific mineralogy, particle shape and relative surface porosity was riffled to obtain 24 gravel specimens, each 100±5g dry mass (Table 2). In the identification of the gravel specimens, A denotes angular, F flaky alone, E elongate alone, and FE both flaky and elongate particle shapes.

Table 2 Gravel test specimens.

MINERALOGY	PARTICLE SHAPE	SPECIMEN
Carboniferous Limestone	Angular	A1
	Flaky alone	F1
	Elongate alone	E1
Sandstone (low porosity)	Angular	A2
	Flaky alone	F2
	Elongate alone	E2
Sandstone (medium to high porosity)	Angular	A3, *A3.1*
	Flaky alone	F3
	Elongate alone	E3, *E3.1*
Silicified limestone	Angular	A4, *A4.1*
	Flaky alone	F4, *F4.1*
	Elongate alone	E4, *E4.1*
Chert	Angular	A5
	Elongate alone	E5, *E5.1*
Siltstone	Flaky and elongate	FE1, *FE1.1*
Quartz, quartzite and microgranite	Angular	A6
	Flaky and elongate	FE2

Experimental Methods

A mortar paste was prepared by thoroughly mixing the silica sand and ordinary Portland cement using a water to cement ratio of 2:1 in the design mix. Due to the relatively small volume of the concrete moulds (100x100x20 mm in size) and the many different gravel specimens, the 24 concrete tablets were prepared by pressing the saturated, surface-dried gravel specimens into the mortar paste that had already been placed in the timber moulds. The tablet thickness of 20 mm meant that the gravel particles would be fully embedded in the mortar paste with minimal cover. The wet concrete tablets were compacted using a vibrating table after which the tops of the tablets were towelled flush with the tops of the moulds, removing any excess mortar. The tablets were then covered with wet burlap and allowed to set over a period of 24 hours after which some of the tablets were wire brushed, exposing the gravel particles nearest the surface. The wire-brushed tablets are listed in italics in Table 2. All of the tablets were then de-moulded and allowed to cure under water at ambient laboratory temperature of 20±2^{o}C over a period of 28 days.

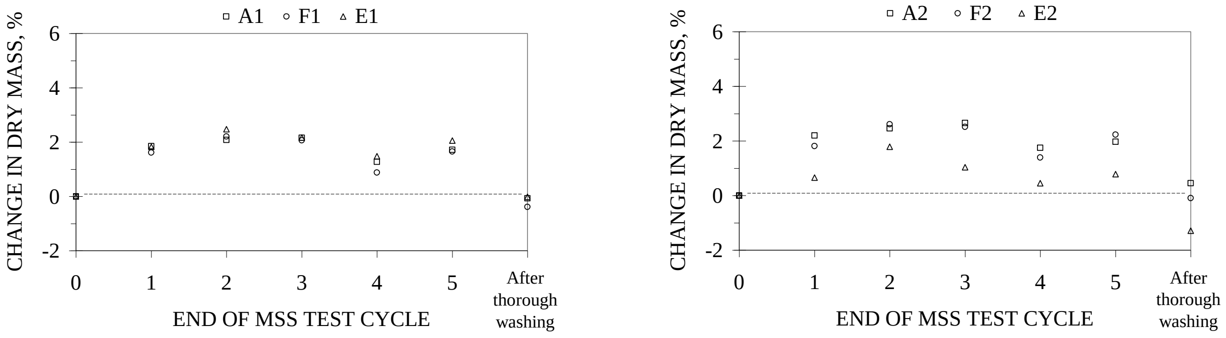
The soundness of the gravel particles set in concrete was assessed following a methodology similar to that of the standard MSS test [1]. The concrete tables were oven dried at a temperature of 105–110^{o}C over a period of 24 hours. The initial dry masses (between 400 and 440 g) were recorded after cooling to ambient laboratory temperature. All of the tablets had similar dry density values of about 2200 kg/m^3.

The tables were then subjected to five cycles of immersion in a supersaturated magnesium sulphate solution and oven drying. Each cycle comprised in turn immersion in salt solution at a temperature of 20±2^{o}C for a period of 17±5 hours; removal from the solution and drip drainage over a period of 2±¼ hours; oven drying at a temperature of 105–110^{o}C for a period of at least 24 hours, and cooling at ambient laboratory temperature for a period of 5 ± ¼ hours. The tablets were thoroughly rinsed with tap water over a period of 72 hours at the end of the fifth cycle. A 5% barium chloride solution was used to check for the presence of residual salt in the tablets. The dry masses of the concrete tablets corresponding to each of the five cycles were recorded. The performance of the concrete mixes and in particular that of any exposed gravel particles were visually examined during the course of the test.

EXPERIMENTAL RESULTS

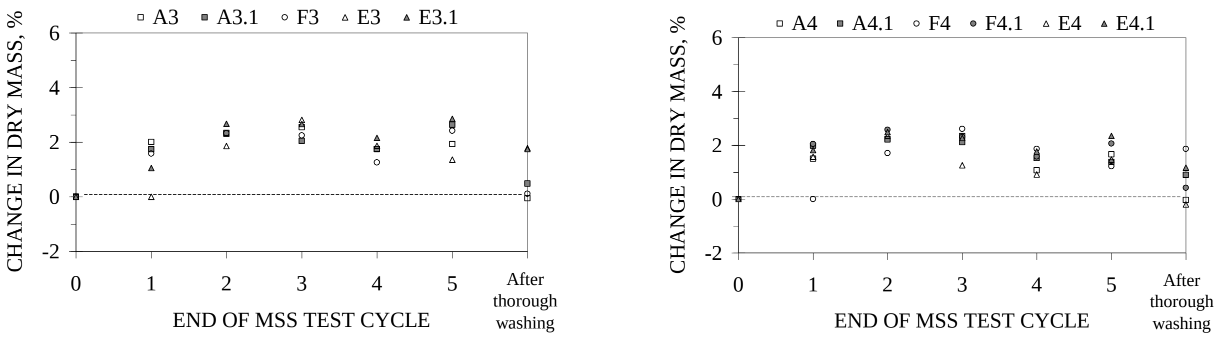
The soundness of the concrete tablets was assessed on the basis of a careful visual inspection and the changes in the oven-dry masses recorded at the end of each cycle of the MSS test. Figure 1 shows the percentage changes in the initial dry masses of the tablets for the different mineralogical constituents. The mean percentage changes in the dry masses are plotted in cases where two or more tablets that comprised gravel particles of the same shape and mineralogy were tested. The closed symbols in the Figure indicate concrete tablets that had been wire brushed prior to the start of the MSS tests.

The marginal difference (which was assumed to be insignificant at the time) in the turbidity of the tap water and the wash water that had been treated with the barium chloride solution seemed to indicate that at the end of the 72 hour rinsing period only small traces of the salt had remained within the pore voids of the concrete tablets.



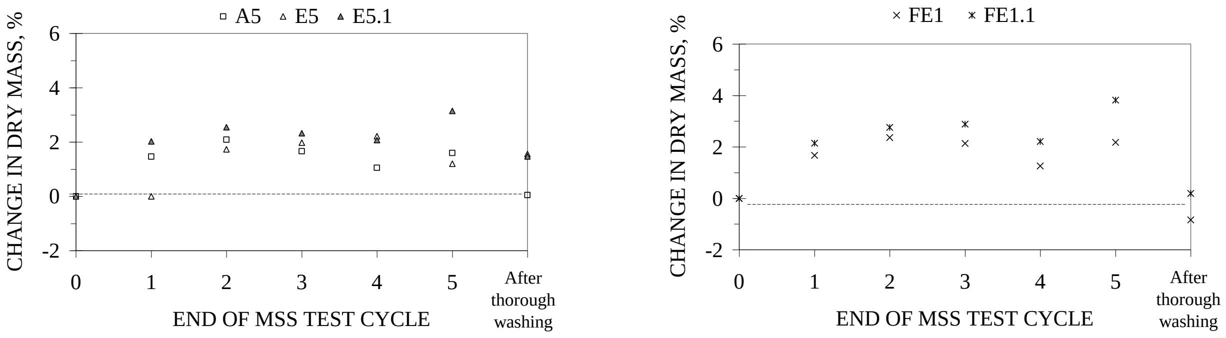
(a) Carboniferous limestone.

(b) Sandstone (low porosity).



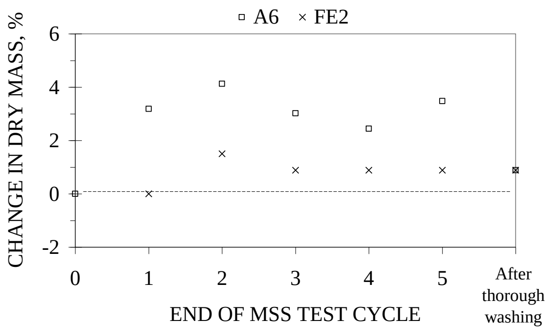
(c) Sandstone (medium to high porosity).

(d) Silicified limestone.



(e) Chert.

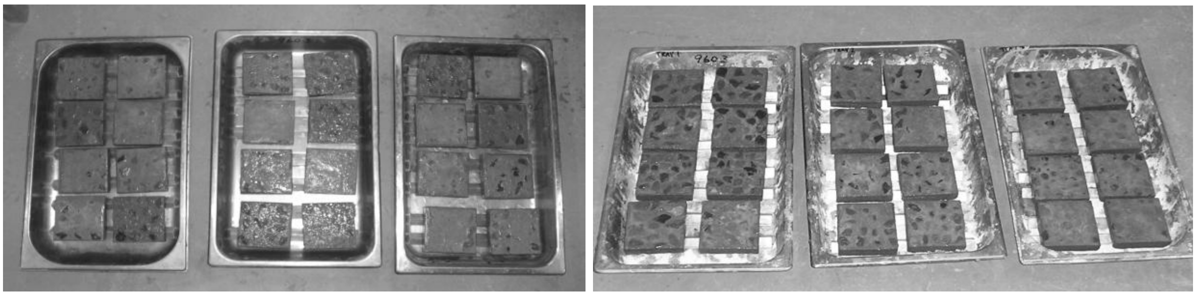
(f) Siltstone.



(g) Quartz, quartzite and micro-granite.

Figure 1 Change in the dry mass of the concrete tablets during the MSS tests.

A careful examination of the tablets by the naked eye confirmed that weathering of both the gravel particles and the cement paste had occurred. The surfaces of the tablets had deteriorated with progressive softening and disintegration of the cement paste. A thin layer of mortar had been stripped away, exposing gravel particles in every tablet by the third cycle of the MSS tests (Figure 2). Some localized weathering/pitting was also observed in the mortar bond even in cases where the gravel particles themselves appeared to be sound (for example, specimens F1 and F4). The degree of weathering experienced by the exposed gravel particles is summarized in Table 3. Some of the effects of the more severe weathering of the particles are shown in Figure 3.

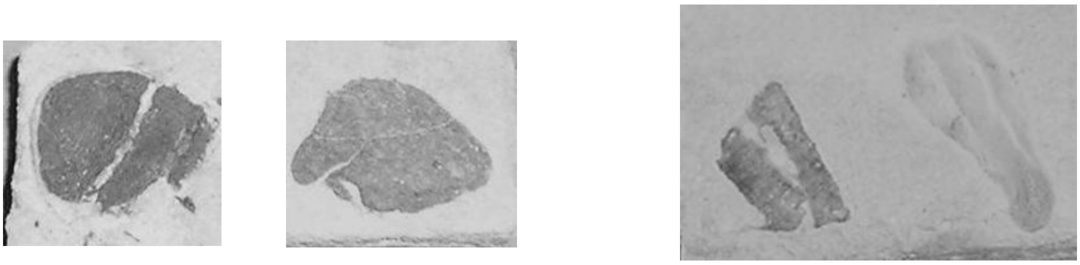


(a) Saturated tablets before MSS tests. (b) Tablets after third cycle of MSS tests.

Figure 2 Surface weathering of the concrete tablets.

Table 3: Conditions of exposed gravel particles by the end of the MSS tests.
Note: concrete tablets wire-brushed prior to MSS testing are listed in italics.

MINERALOGY	SPECIMEN	CONDITION OF GRAVEL PARTICLES
Carboniferous Limestone	A1	No damage visible
	F1	No damage visible to particles but some pitting in mortar bond
	E1	No damage visible
Sandstone (low porosity)	A2	Slight weathering of the particle surface only
	F2	Few hairline cracks
	E2	Some strong cracks
Sandstone (medium to high porosity)	A3	Few hairline cracks
	A3.1	Some strong cracks
	F3	Some strong cracks
	E3	Some strong cracks
	E3.1	Some strong cracks
Silicified limestone	A4	No damage visible
	A4.1	No damage visible
	F4	Few hairline cracks to particles and some pitting in mortar bond
	F4.1	Few hairlinecracks and slight pitting of particles and mortar bond
	E4	No damage visible
	E4.1	No damage visible
Chert	A5	No damage visible
	E5	No damage visible
	E5.1	No damage visible
Siltstone	FE1	Severe weathering and disintigration
	FE1.1	Some severe weathering and disintigration
Quartz, quartzite and microgranite	A6	Slight weathering of the particle surface only
	FE2	Slight pitting of particle surface only



(a) Angular, high porosity sandstone.

(b) Elongate, low porosity sandstone.

(c) Flaky, high porosity sandstone.

(d) Siltstone.

Figure 3 Examples of severe weathering of some particles.
(Scale: actual gravel particles 14–20 mm size).

ANALYSIS AND DISCUSSION

Overall, a marginal gain of up to about 3.0% dry mass occurred by the end of the second or third cycle of the MSS tests which was most likely due to the filling of the pore voids (and hence the densification of the mortar matrix) by residual crystalline salt and/or the expansive reaction products (salt weathering comprises both mechanical and chemical degradation). Similar behaviour has been reported in testing reinforced concrete in magnesium-sodium sulphate solutions [4]. The dry mass of the tablets began to decrease by the fourth cycle due to progressive softening and disintegration of the mortar and exposed, unsound gravel particles as well as localized pitting in the mortar bond. Overall, for practical purposes there was no net change in the dry mass of the tablets by the end of the test. Exceptions included the siltstone (FE1) and low-porosity sandstone (F2) tablets in which the weathering had been more severe (small net reductions of 0.8 and 1.3% dry mass, respectively). Conversely, all of the wire-brushed tablets experienced marginal gains in dry mass compared to those tablets with fully embedded gravel particles at the start of the test. This most likely occurred due to the greater weathering effects of the salt solution on the mortar matrix.

The visual examination was much more conclusive with the appearance of the exposed gravel particles giving a clearer indication of the weathering effects than the gravimetric measurements. Referring to Table 3, the carboniferous limestone, silicified limestone, chert, quartz, quartzite, and micro-granite particles were all sound. The exposed sandstone particles experienced some weathering effects; the severity appeared to be related to the surface porosity and shape of the particle. The low-porosity sandstone particles were of marginal soundness whereas the medium to high porosity sandstone particles (high water absorption) tended to be unsound. The siltstone particles had been severely weathered and hence unsound. These responses mirror those reported for the loose constituents during MSS testing [3]. In some instances, the mortar bond was a favoured location for corrosive attack resulting in localized pitting even around sound gravel particles (for example, limestone and silicified limestone tablets, F1 and F4, respectively).

CONCLUSIONS

The findings of the laboratory test programme indicate that:

1) The performance of the loose gravel in the magnesium sulphate soundness (MSS) test was a good indicator of the performance of the gravel particles set in concrete.

2) The assessment of the concrete soundness relied on the visual examination. Assessments based on the difference in the masses recorded at the start and end of the MSS tests were inconclusive since the mass losses experienced due to weathering effects tended to be negated by residual salt and/or expansive reaction products that remaining in the pore voids.

3) Overall, the carboniferous limestone, silicified limestone, chert, quartz, quartzite and micro-granite particles were all sound. The low porosity sandstone particles tended to be of marginal soundness whereas the medium to high porosity sandstone and particularly the siltstone particles (high water absorption) were unsound.

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