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Behaviour of soil–cement specimens in unconfined dynamic compression

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The response of the cement-stabilized red marl to dynamic loading in compression has been investigated over a range of cement contents and curing times. Specimens were subjected to different stress levels below unconfined compressive strength, at a frequency of 5 Hz, and a fatigue relationship for the material was developed. The value of resilient modulus was found to be greater than the modulus of elasticity for the same cement content and curing time.

1. Introduction

Studies of the structural failure of the soil–cement roadbase caused by repeated traffic loads, which includes fatigue failure, confirm that the failure occurs due to development of cracks in fatigue without any apparent permanent deformation in pavements. Pretorius [1], for example, reports loss in road-carrying capacity of the soil–cement roadbase due to infiltration of water through fatigue cracks. It is therefore essential to design the soil–cement pavement to withstand the dynamic action of traffic loads with longer fatigue life. In many areas around the world there has been a rapid increase in traffic loads and volume which has led to a realization of the inadequacy of the present design methods.

The development of analytical design criteria to enable soil–cement pavements to withstand fatigue effects caused by repeated traffic loads, has been considered by several investigators [2–4]. There are, however, limitations to the generalized design approach because of many variables affecting the determination of characteristic values of design parameters. Limited information regarding tensile and fatigue characteristics of soil–cement contributes to these difficulties.

The soil–cement process involving chemical stabilization was developed from the technology of soil mechanics to provide a means of increasing the shear strength of soil. The technique involves breaking up the soil, mixing in cement, watering and compacting. An analogy can be drawn with concrete which is normally made from batched coarse and fine aggregates and cement. The cement particles surrounding the soil granules act as bridges, bonding the soil granules together, and causing an increase in strength of the soil–cement mix. For clays, the rate of increase in shear strength becomes greater as the cement content is increased.

Modification of the material must be carried out with two important parameters in mind: the cost of the material modification, and the life of the structure over which the cost may be recovered. The cost of the material modification will depend on the cement content and the compactive effort required to produce an acceptable material. The normal practice is to use ordinary Portland cement, and the cement content is usually determined by measuring the unconfined compressive strengths. In the UK, a minimum strength of 2.76 $\mathrm{MN\,m^{-2}}$ at 7 days is required for moist-cured cylindrical specimens having a height/diameter ratio of 2:1. The minimum cement content required to stabilize the red marl used in this investigation is approximately 6%. It is generally accepted that the full-scale field-mixing process is less efficient than the closely controlled laboratory technique, and hence it is common practice to increase the laboratory-determined cement content by a factor of ~ 1.5 to give a cement content appropriate in the field. Typical values of cement content as a percentage by weight vary from 2–4 for granular soils to 10–15 for clays [5]. It is known that soils have been stabilized with a cement content as low as 4%, but sometimes as much as 20–25% may be required. The high percentage of stabilizer, however, will result not only in higher costs but also in more brittle material, which will be more susceptible to fatigue cracking.

Other cement-bound materials used in the roadbase construction are lean concrete and cement-bound granular materials, which are generally used in roads with medium-to-heavy levels of traffic. Crack growth in roadbases is a major problem, and it is accepted practice that a stronger cement-bound material of substantial thickness, adequately cured, will help to control cracking in these structures. The use of cement to stabilize clay subject to dynamic loads is very effective in increasing the rigidity of the soil and in reducing the deformation. In general, an increase in cement content increases damping and dissipates larger wave energy. This is an advantage in the practical

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design of pavements because of reduction in amplitude of vibration.

The purpose of the research reported here was to investigate two variables, cement content and curing time, and their effects on the resilience and fatigue characteristics of soil–cement specimens under dynamic loading.

2. Experimental procedure

2.1. Material properties and specimen preparation

The red marl from Abergaveny, South Wales, UK, was air dried, mechanically pulverized to a maximum 2 mm diameter clod size, and well mixed before carrying out routine classification tests according to BS 1377:1975 [6]. The following values were obtained:

Liquid limit, 37%
Plastic limit, 19%
Plastic index, 18%
Specific gravity, 2.7
Particle size distribution: sand 9%, silt 28%, clay 63%, organic matter, negligible.

The Proctor compaction test was carried out to determine the dry density/moisture-content relationship of the soil using a 2.5 kg rammer according to BS 1377:1975, test 12 [6]. This test is often referred to as standard BS compaction, and is the heavy compaction used for airfield construction. The optimum moisture content and the maximum dry density were found to be 15% and 1.85 $\mathrm{Mg\,m^{-3}}$, respectively.

The oven-dried soil–cement mixture was first thoroughly dry mixed, and then a predetermined amount of distilled water was slowly added to obtain a moisture content at a consistent value of 15% just prior to moulding. In order to produce a consistent and homogeneous mix, various mixing techniques and times have been investigated. It was found that a soil–cement mixture mixed in a SE–401 Hobart mixer fitted with a beater blade for exactly 11 min on the speed 1 setting produces the best results. The mixing times investigated were from 8–13 min at 1-min intervals. The shorter mixing time resulted in specimens having an excessive amount of flaws, and the longer time did not result in any significant enhancement of the quality of the specimen, but required a higher energy consumption and a longer production time.

The cylindrical specimens were prepared according to BS 1924:1975, test 10 [6]. The mould consisted of a tapered steel body of internal dimensions 100 × 50 mm mean diameter, two steel plugs, and displacing collars and ejection plunger. To minimize friction, all specimens were prepared by two-end static compaction in an oil-lined mould. After compaction, two end plugs on the specimen were removed and the carefully extruded specimen was weighed to the nearest 0.1 g, its surface smoothness inspected and the dimensions measured to the nearest 0.01 mm. This quality control was necessary in order to consistently monitor the uniformity of the mix. The specimen was then wrapped immediately in a polythene sheet, which adhered to its damp surface, and then in aluminium foil to ensure constant temperature distribution around the specimen. Finally the specimen was placed in a plastic container to prevent any moisture changes. The curing was carried out by placing specimens inside a controlled-environment chamber at 25 °C and a constant relative humidity of not less than 98%. The specimens were prepared in batches of ten. Fifteen batches in all were prepared with cement content of 6, 10, 14, 18 and 22%, and curing periods of 7, 14 and 28 days were used. Two specimens from each batch were tested in order to determine the unconfined compressive strength of the particular mix.

2.2. Testing equipment and procedure

Dynamic unconfined compression tests were carried out on the Instron 1251 testing machine. The dynamic displacement mode with sinusoidal loading was selected and set from almost zero load to a load level less than that which would cause failure in static mode. The frequency of 5 Hz was chosen to simulate traffic loading. The number of repetitions was monitored on a cycle counter and an automatic chart recorder was used to indicate the waveform, frequency and applied load.

One of the difficulties experienced during this research was the measurement of deformations. The soil–cement materials are far stiffer and more brittle than compacted soils. The amount of measurable deformation under dynamic load is of the order of 0.01% strain axially and 0.001% strain laterally. The transducer assembly which complies with these requirements is shown in Fig. 1, and was developed at the University of Glamorgan. It consists of four Linear Variable Differential Transducers (LVDT) (manufactured by Sangamo) capable of measuring deformations around ± 1 mm, which is very accurate. LVDTs of even higher accuracy, ± 0.25 mm, were attached to the side of the specimens to measure the lateral deformations.

The dynamic tests were carried out in such a way that various percentages of the load at failure in the static test were applied dynamically in load-control mode at a frequency of 5 Hz. The number of load repetitions to failure was recorded, and if the failure had not occurred by 100 000 cycles, the cyclic loading was switched off. The final and residual lateral deformations occurring during the test were monitored by means of the transducer assembly and recorded by the Instron recorder.

When carrying out the compression tests, it was essential to reduce the friction between the specimen surface and the end cups. This was achieved by applying silicone grease to the contact areas and then polishing with a graphite powder. A smooth surface thus created reduced the amount of friction between the specimen and the cups and consequently prevented the excessive bulging of the specimen.

3. Results

3.1. Unconfined dynamic compression tests

The response of the cement-stabilized red marl to dynamic loading in compression was investigated over

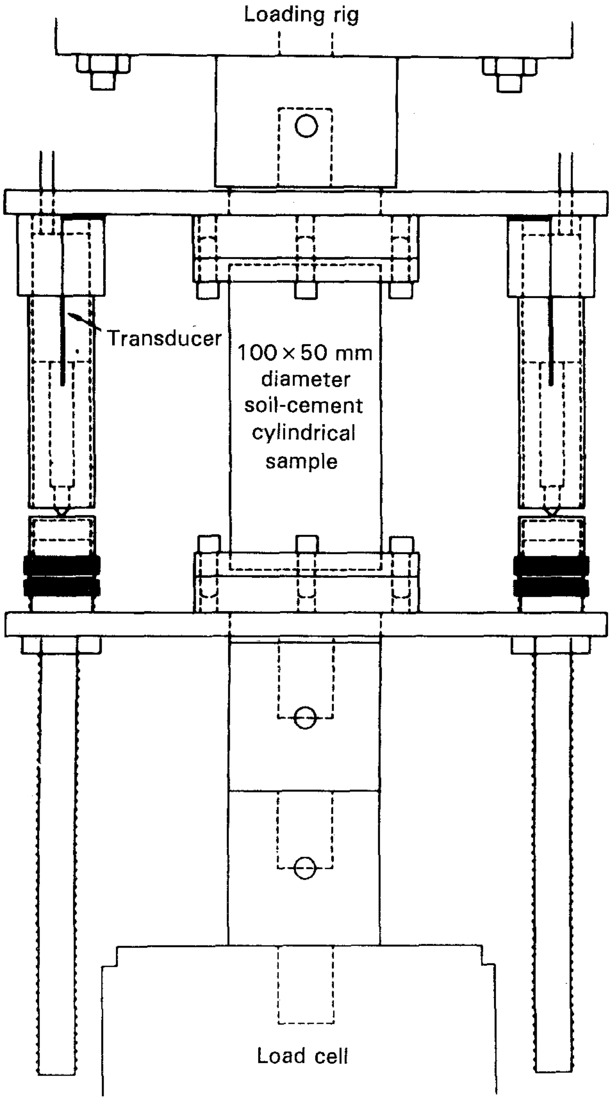

Figure 1 Transducer assembly system for dynamic tests.

a range of cement contents and curing times. In order to develop a fatigue relationship for the material, all specimens were subjected to different stress levels below unconfined compressive strength, at a frequency of 5 Hz. The results of these tests are given in Tables I–III. The results indicating a relationship between the dynamic compression and curing time are presented in Figs 2–4.

A comparison of the rate of the compressive stress fall-off to cause failure is shown in Fig. 5. For clarity only two extreme results are shown, i.e. specimens with 6% and 22% cement content, respectively. It can be seen that the rate of the stress fall-off for specimens with higher cement content is faster. This indicates that the richer mixes tend to be more brittle and hence more susceptible to fatigue cracking. Linear regression analyses [7] were performed using the VAX computer in order to determine the relationships between compressive stress applied, curing time and number of cycles to failure for various cement contents. The fatigue failure relationship can be written as

$$CS = J + K \log 10 N_{\mathrm{f}} \qquad (1)$$

where CS = compressive stress; J = ordinate coefficient of the best polynomial; K = slope coefficient; and N_{f} = number of load cycles to failure. The numerical values of coefficients J and K are given in Tables IV and V.

Equation 1 was used to estimate compressive stress under fatigue loading and the results are summarized in Tables I–III.

TABLE I Dynamic compression test results for 7 days' curing

Cement content (%)	Stress ($\mathrm{N\,mm^{-2}}$)	Stress (%)	Cycles to failure (no.)	Log10 cycles to failure
6	2.49	100.00	1	0
	2.29	91.95	3600	3.56
	2.04	81.73	100000	5
10	3.42	100.00	1	0
	3.06	89.37	454	2.66
	2.80	81.92	100000	5
14	4.45	100.00	1	0
	4.25	95.49	197	2.29
	4.00	89.84	391	2.59
	4.04	90.82	1729	3.24
	3.75	84.22	100000	5
18	5.68	100.00	1	0
	5.35	94.14	55	1.74
	5.09	89.65	95	1.98
	4.84	85.17	366	2.56
	4.59	80.69	344	2.54
	4.33	76.21	100000	5
22	7.63	100.00	1	0
	7.13	93.46	19	1.28
	6.88	90.12	80	1.90
	6.62	86.78	52	1.72
	6.37	83.44	558	2.75
	6.11	80.11	1000	3
	5.86	76.77	1539	3.19
	5.60	73.43	100000	5

TABLE II Dynamic compression test results for 14 days' curing

Cement content (%)	Stress ($\mathrm{N\,mm^{-2}}$)	Stress (%)	Cycles to failure (no.)	Log10 cycles to failure
6	2.85	100.00	1	0
	2.80	98.18	82	1.91
	2.56	89.64	821	2.91
	2.31	81.07	100000	5
10	3.80	100.00	1	0
	3.50	92.02	43	1.63
	3.25	85.44	212	2.33
	3.00	78.87	100000	5
14	5.41	100.00	1	0
	5.09	94.07	15	1.18
	4.84	89.37	33	1.52
	4.58	84.67	57	1.76
	4.33	79.96	111	2.05
	4.07	75.26	100000	5
18	6.53	100.00	1	0
	6.11	93.53	47	1.67
	5.86	89.63	142	2.15
	5.60	85.74	188	2.27
	5.35	81.84	35625	4.55
	5.09	77.94	100000	5
22	8.11	100.00	1	0
	7.64	94.17	100	2
	7.13	87.89	157	2.20
	6.62	81.61	1960	3.29
	6.11	75.34	2036	3.31
	5.86	72.20	100000	5

TABLE III Dynamic compression test results for 28 days' curing

Cement content (%)	Stress (N mm^{-2})	Stress (%)	Cycles to failure (no.)	Log10 cycles to failure
6	2.99	100.00	1	0
	2.80	93.73	64	1.81
	2.67	89.47	1100	3.04
	2.67	89.47	1750	3.24
	2.55	85.21	100000	5
10	4.20	100.00	1	0
	4.07	96.99	47	1.67
	3.82	90.93	224	2.35
	3.57	84.87	415	2.62
	3.31	78.80	100000	5
14	5.62	100.00	1	0
	5.09	90.66	33	1.52
	4.84	86.13	2012	3.30
	4.58	81.60	100000	5
18	7.45	100.00	1	0
	7.13	95.69	38	1.58
	6.88	92.28	50	1.70
	6.62	88.86	67	1.83
	6.37	85.44	81	1.91
	6.11	82.02	517	2.71
	5.60	75.19	100000	5
22	8.88	100.00	1	0
	8.15	91.74	138	2.14
	7.64	86.01	563	2.75
	7.13	80.28	23673	4.37
	6.62	74.54	100000	5

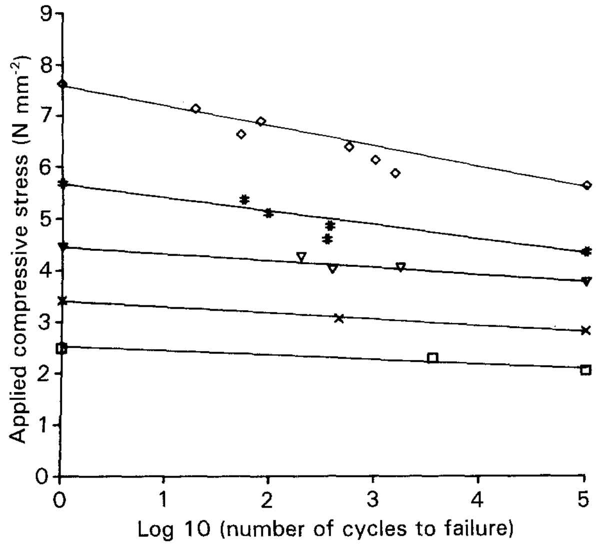

Figure 2 Dynamic compression tests 7 days' curing time. Cement content, □, 6; ×, 10; ▽, 14; #, 18; ◇, 22%.

3.2. Resilient modulus test

The relationship between the resilient modulus and log10 number of cycles is shown in Figs 6 and 7. These graphs represent typical test results obtained from samples having the same cement content and curing time, but subjected to two different stress levels. Fig. 6 shows test data for the specimen subjected to a stress level of 3.56 N mm^{-2}, which was equivalent to 85% of the static unconfined compressive strength. The resilient modulus, initially at 2250 N mm^{-2}, started to decrease over the range of the first 100 load cycles, and then it remained almost constant for 200 load cycles.

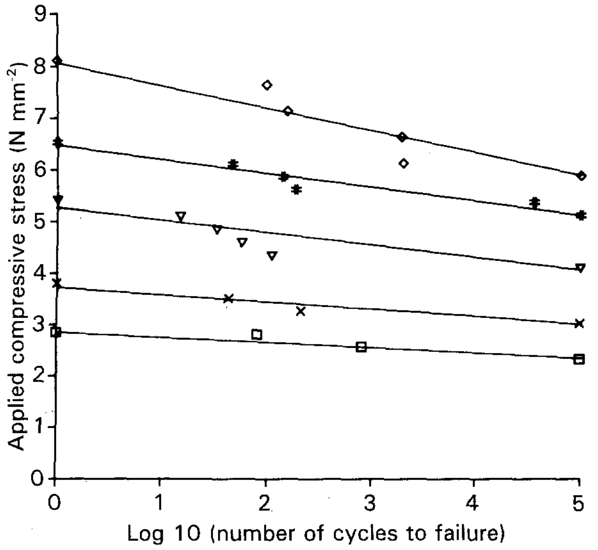

Figure 3 Dynamic compression tests, 14 days' curing time. Cement content, □, 6; ×, 10; ▽, 14; #, 18; ◇, 22%.

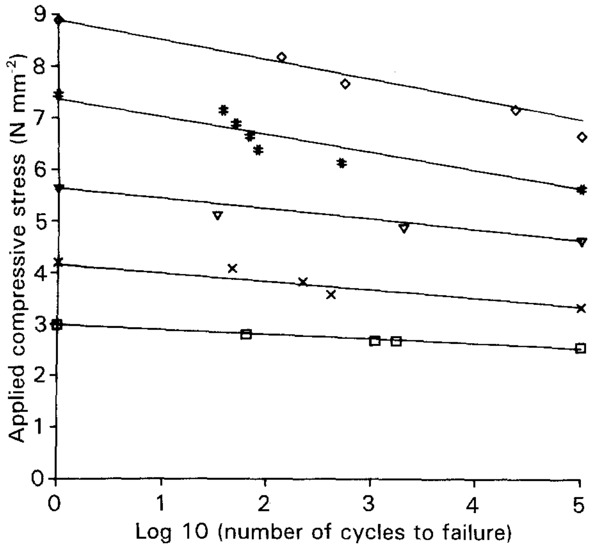

Figure 4 Dynamic compression tests, 28 days' curing time. Cement content, □, 6; ×, 10; ▽, 14; #, 18; ◇, 22%.

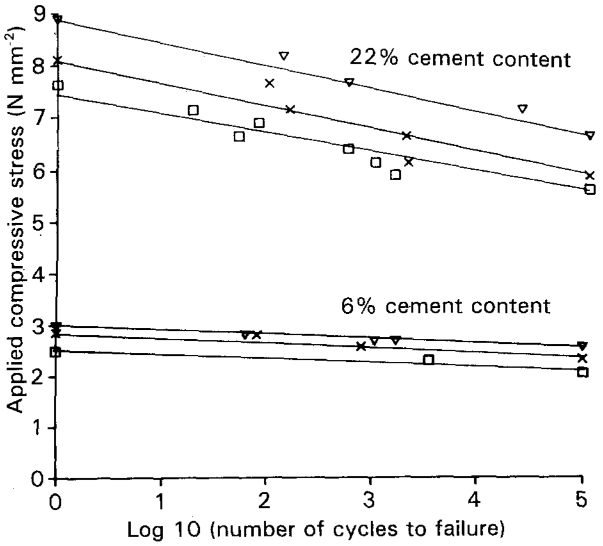

Figure 5 Fatigue performance of 6 and 22% cement content soil–cement at □, 7; ×, 14; and ▽, 28 days' curing time.

TABLE IV Ordinate coefficient of the best polynomial, J, for various cement contents and curing times

Curing time (days)	J coefficient for cement contents (%) of				
	6	10	14	18	22
7	2.515	3.408	4.470	5.643	7.551
14	2.910	3.747	5.337	6.464	8.216
28	2.971	4.193	5.521	7.410	8.942

TABLE V Slope coefficient, K, for various cement contents and curing times

Curing time (days)	K coefficient for cement contents (%) of				
	6	10	14	18	22
7	− 0.085	− 0.124	− 0.141	− 0.290	− 0.436
14	− 0.114	− 0.161	− 0.264	− 0.270	− 0.495
28	− 0.089	− 0.194	− 0.198	− 0.388	− 0.441

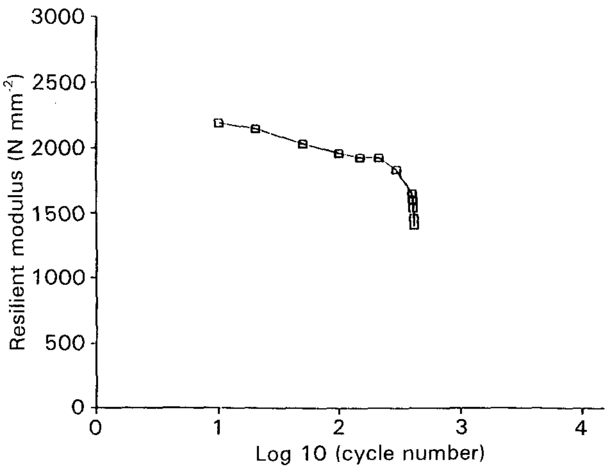

Figure 6 Variation of the resilient modulus with log10 cycle no., at 3.56 N mm^{-2} stress level.

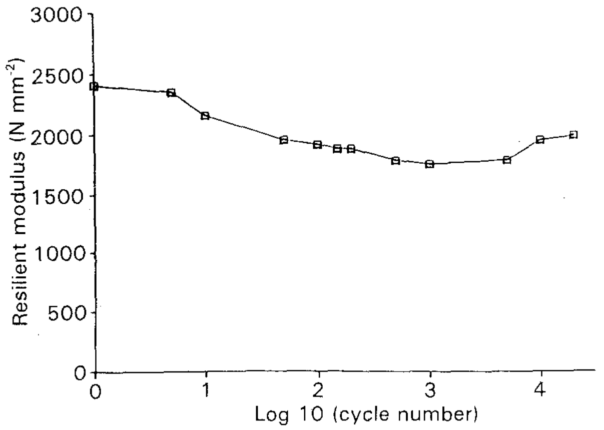

Figure 7 Variation of the resilient modulus with log10 cycle no., at 3.31 N mm^{-2}.

TABLE VI Comparison of the modulus of elasticity (E) and resilient modulus (RM) for various curing times and cement contents

Curing time (days)	E (N mm^2)		RM (N mm^2)	
	10%	18%	10%	18%
7	800	1444	849	1732
14	852	1648	1429	3104
28	1220	1939	2250	3275

During this period microcracks started to develop and the resilient modulus began to drop rapidly to a failure point at 415 cycles. Fig. 7 shows test results for the specimen subjected to a stress level of 3.31 N mm^{-2}, which was equivalent to 79% of the static unconfined compressive strength. The resilient modulus, initially at 2400 N mm^{-2}, gradually decreased until 1000 load cycles and then remained constant up to about 6000 load cycles. It was noted that no microcracks developed at this stage. After that the resilient modulus increased slowly and stabilized at about 2250 N mm^{-2} after 30 000 load cycles. Very similar behaviour was observed in other dynamic compression tests.

The resilient modulus concept is generally used in analyses of the dynamic tests results on soils, granular materials and cement-treated soils, and is regarded as analogous to the modulus of elasticity for static tests. Table VI summarizes the values of the resilient modulus and the modulus of elasticity for the mixes with 10 and 18% cement content (CC) and after 7, 14 and 28 days curing time. The results show that the values of the resilient modulus are higher than the elastic modulus for the same mix and curing time.

4. Conclusions

The response of the cement-stabilized red marl to dynamic loading in unconfined compression was investigated over a range of cement contents and curing times. It was found that the damage induced by dynamic loading in compression was primarily in the form of extensive microcracks on the surface of the cylindrical specimens (see Fig. 8). It should be remembered, however, that the tests reported in this paper employed only repetitive compressive stress applications with fixed principal planes, whereas the actual roadbase behaviour probably involves not only tensile stress states, but also a rotation of principal planes as the moving wheel passes over a fixed point.

The relationship between applied compressive stress and number of load cycles is given by Equation 1. This equation can be used effectively in predicting a level of compressive stress generated in specimens made from a similar soil–cement mix as described in this paper. It is shown that the rate of the compressive stress fall-off to cause failure is faster in specimens with higher cement content. This phenomenon is mainly due to the fact that the increased cement content increases the brittleness of the material. The practical conclusion which can be drawn from this study is that the values of the resilient modulus determined from the dynamic compression tests confirmed the general trend, indicating that the resilient modulus is higher than the elastic modulus for the same cement content and curing time.

Figure 8 Cylindrical specimen showing microcracks and mode of failure.

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