

CHAPTER 4

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APPENDIX A

LABORATORY PROCEDURE, MINERALOGY AND PETROLOGY FOR
GRANITE AND ANDESITE ROCKSA1 Preparation of Granite and Andesite Rock Boulders
and Cores

The boulders of granite were approximately 300 x 300 x 250 mm. It was found that boulders in excess of these dimensions proved cumbersome and difficult to manoeuvre when mounted on the drilling machine.

The boulders were mounted on a wooden board and secured by placing nails around the perimeter of the base of the rock and then applying Plaster of Paris around the base of the boulder, filling up voids between the rock and the wooden board. The boulders were chosen to be as cuboid as possible, or to have at least two opposite faces flat. This facilitated both fixing and drilling. The boulders were ready for drilling approximately one hour after the Plaster of Paris was applied.

As stated in the text, the drilling machine was a Matheys vertical coring machine and the drill bit and barrel was NX type, nominal diameter 42 mm.

A2 Drilling procedure for Granite rock

The prepared boulder was placed on the adjustable table of the coring machine and the height adjusted by means of a manual worm gear. Great care was exercised during this operation to prevent damage to the drill bit. Once the boulder was in the correct position, a steady flow of water was applied through the core barrel. Immediately prior to the machine being switched on, the core bit was elevated above the surface of the rock to prevent damage.

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After the machine was switched on, the core bit was applied to the rock by a drilling lever. A steady pressure was maintained while the core was cut from the rock. It was found that during the drilling procedure the drill bit would at times cut through the rock with ease and at other times considerable force had to be applied to drill the core. This was evident on individual cores and throughout the rock. This could be attributed to two possibilities.

- a) inclusions of 'harder' rock in the granite matrix.
- b) the cutting edge of the drill piece had collected a film of rock over its diamond abrasive cutting edge.

Therefore, to ensure (b) did not occur it was necessary to clean the drill bit by drilling into an abrasive rock such as sandstone which effectively 'cleans' the drill bit and exposes fresh diamond cutting edges. This procedure was performed at the discretion of the operator. However, cleaning the drill bit between each core facilitated the drilling operation.

A3 Grinding and lapping of Granite cores

The unfinished cores were cut to a minimum aspect ratio of 2:1 (but not greater than 2,5:1) by use of a Diamant Boart saw DV20. Approximately 1mm extra on the length of each cut core was allowed for, to compensate for the lapping and grinding procedure.

The cut cores were fixed into the disc of the lapping machine, (refer to figure 1.6) and the specimens ground flush by means of silicon abrasive filings and a water lubricant. The disc is traversed across the rotating lapping wheel onto which are applied the abrasive filings and lubricating water.

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The procedure is complete when a grey slurry is produced which is very fine and almost fluid. After grinding one set of ends the disc shown in figure 1.6 was completely inverted with the specimens fixed in position to ensure that the ends of the specimens were not only flat but also parallel. It is also recommended to grind a balanced number of specimens at any one time on the lapping machine. The disc holds six specimens in a hexagonal configuration.

The completed cores were then wiped off and left to dry. A straight edge of a steel ruler was held across each end to ensure the specimen was plane.

A4 Preparation of Andesite boulders and cores

The andesite boulders were of similar dimension to those of the granite. Due to the hardness of the andesite rock, the cores were cut by Boart Research Ltd. A high powered industrial drilling machine was used to cut the required number of cores from the andesite boulders supplied.

A5 Grading Analysis and Specific Gravity Tests for Granite and Andesite Aggregate

In order to classify the two aggregates used, a sieve grading analysis and a specific gravity test was carried out on each aggregate type. The specific gravity was determined three times and the average was found to be 2.89 for the andesite sand and 2.65 for the granite sand. The gradings of the granite and andesite crusher sands as received from the quarries are shown in tables A1 (a) and (b) respectively. The values shown in these tables represent the average of three grading determinations. These gradings are also shown graphically on figures A1(a) and (b) respectively.

Table A1 (a) Grading Analysis of Granite Crusher Sand as Received from the Crusher

SIEVE SIZE m	% RETAINED	% PASSING	CUMULATIVE % RETAINED
4750	0,3	99,7	0,3
2360	11,9	97,8	12,2
1180	19,4	68,4	31,6
600	20,4	48,0	52,0
300	19,7	28,3	71,7
150	16,4	11,9	88,1
75	6,8	5,1	94,9
< 75	5,1	-	-
TOTALS	100,0		255,9

FINENESS MODULUS = 2,56

Table A1 (b) Grading Analysis of Andesite Crusher Sand as Received from the Crusher

SIEVE SIZE m	% RETAINED	% PASSING	CUMULATIVE % RETAINED
4750	0,4	99,6	0,4
2360	20,7	78,9	21,1
1180	24,9	54,0	46,0
600	15,5	38,5	61,5
300	9,4	29,1	70,9
150	6,6	22,5	77,5
75	4,6	17,9	82,1
< 75	17,9	-	-
TOTALS	100,0		277,4

FINENESS MODULUS = 2,77

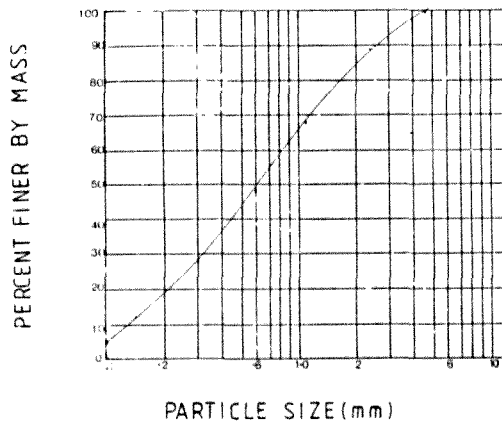


Figure A1(a) Grading Curve for Granite Sand as Received from Crusher

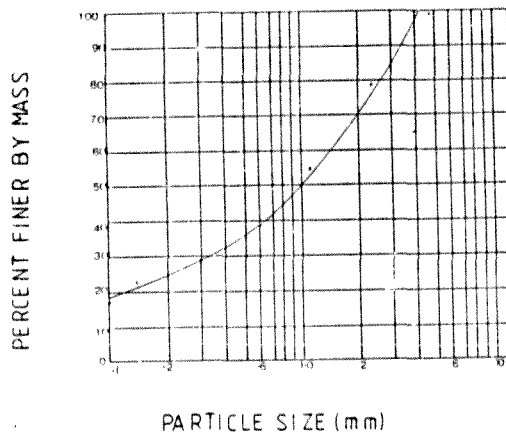


Figure A1 (b) Grading Curve for Andesite Sand as Received from Crusher

APPENDIX B

REPEATABILITY OF DYNAMIC ROCK CORE RESULTS.
DYNAMIC ROCK CORE RESULTS FOR GRANITE AND ANDESITE.

B1 Definitions

For the purposes of this appendix the following definitions apply:

repeatability (r) : Quantitative expression of the random error associated with a single test operator in a given laboratory obtaining successive results with the same apparatus under constant operating conditions on identical test material. It is defined as that difference between two such single results as would be expected in the long run in only one case in twenty in the normal and correct operation of the test method;

reproducibility (R) : Quantitative expression of the random error associated with test operators working in different laboratories, each obtaining single results on identical test material when applying the same method. It is defined as that difference between two such single and independent results as would be exceeded in the long run in only one case in twenty in the normal and correct operation of the test method.

B2 Repeatability of Dynamic Results

From the above definitions a repeatability test, rather than a reproducibility test was carried out on an andesite core to try and gauge some measure of the repeatability of the equipment used and the accuracy of measurements taken. Table B1 shows the travel times of both the P- and S- wave for this specimen measured twenty successive times. It is clear that the P- wave can be measured with greater accuracy than the S- wave. This highlights the fact that the S- wave

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travel time must be measured very carefully and as precisely as possible. The greatest source of error in measuring dynamic constants in this way is the estimated S-wave travel time.

B3 Dynamic Rock Core Results

See tables B2 and B3 for granite and andesite rocks respectively.

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Table B1 Repeatability of results (P- and S- Wave Travel
Times taken on an Andesite Core 20 Times)

Reading	<u>CORE AC2</u>	
	T_p μs	T_s μs
1.	13,6	26,5
2.	13,6	26,2
3.	13,6	26,2
4.	13,6	26,5
5.	13,6	26,5
6.	13,6	26,5
7.	13,6	26,5
8.	13,6	25,9
9.	13,6	26,2
10.	13,6	27,0
11.	13,6	26,2
12.	13,6	26,0
13.	13,6	26,2
14.	13,6	26,2
15.	13,6	26,2
16.	13,6	26,0
17.	13,6	26,2
18.	13,6	25,9
19.	13,6	27,0
20.	13,6	26,5

Mean T_p = 13,6 μs

Mean T_s = 26,4 μs

Standard Deviation = 0,022 μs Standard Deviation = 0,323 μs

Table B2 Transmission of body waves through Granite rock specimens

MATERIAL	SPECIMEN NUMBER	LENGTH m	DIAMETER m	VOLUME $\times 10^{-4}$ m^3	MASS kg	DENSITY kg/m^3	TRANSMISSION TIMES (T)					
							T_p			T_s		
							Measured μs	Corrected μs	T_p measured μs	Corrected μs	T_s measured μs	Corrected μs
GRANITE	JA1	0,083	0,042	1,123	0,3085	2747,4	15,0	13,7	30,0	25,4		
	JA2	0,084	0,042	1,148	0,3090	2692,0	16,0	14,7	30,0	25,4		
	JA3	0,083	0,042	1,130	0,2987	2642,5	18,0	16,7	40,0	35,4		
	JA4	0,084	0,042	1,148	0,3030	2639,2	16,8	15,5	37,5	32,9		
	JA5	0,084	0,042	1,150	0,3038	2642,4	15,6	14,3	30,0	25,4		
	JA6	0,083	0,042	1,137	0,3113	2736,0	14,4	13,1	28,0	23,4		
	JA7	0,083	0,042	1,132	0,2968	2622,6	15,6	14,3	31,0	26,4		
	JA8	0,082	0,042	1,113	0,2924	2626,9	15,2	13,9	30,0	25,4		

NB: Correction times for pulsing heads:

P-Wave - 1,3 μsec S-Wave - 4,6 μsec where T_p = travel time for P-wave
 T_s = travel time for S-wave

Table B2 Transmission of body waves through Granite rock specimens /continued

MATERIAL	SPECIMEN NUMBER	LENGTH m	DIAMETER m	VOLUME $\times 10^{-4}$ m^3	MASS kg	DENSITY kg/m^3	TRANSMISSION TIMES (T)			
							T_p		T_s	
							Measured μs	Corrected μs	Measured μs	Corrected μs
GRANITE	JA9	0,083	0,042	1,140	0,3016	2646,3	14,6	13,3	29,0	24,4
	JA10	0,083	0,042	1,138	0,3006	2641,2	15,2	13,9	29,0	24,4
	JC1	0,084	0,042	1,150	0,3034	2638,4	15,2	13,9	30,0	25,4
	JC2	0,083	0,042	1,139	0,3020	2650,6	14,8	13,5	30,0	25,4
	JC3	0,084	0,042	1,149	0,3470	2650,8	14,4	13,1	29,0	24,4
	JC4	0,084	0,042	1,140	0,3026	2654,7	14,8	13,5	29,5	24,9
	JF1	0,083	0,042	1,120	0,3033	2709,1	15,6	14,3	31,0	26,4
	JF2	0,083	0,042	1,120	0,3025	2700,4	15,2	13,9	30,0	25,4

NB: Correction times for pulsing heads:

P-Wave - 1,3 μsec S-Wave - 4,6 μsec where T_p = travel time for P-wave T_s = travel time for S-wave

Table B2 Transmission of body waves through Granite rock specimens /continued

MATERIAL	SPECIMEN NUMBER	LENGTH	DIAMETER	VOLUME	MASS	DENSITY	TRANSMISSION TIMES (T)			
							T_p		T_s	
				$\times 10^{-4}$ m^3	kg	kg/m^3	Measured μs	Corrected μs	Measured μs	Corrected μs
GRANITE	JF3	0,081	0,042	1,103	0,2920	2646,2	16,0	14,7	31,0	26,4
	JF4	0,083	0,042	1,121	0,3028	2701,4	15,2	13,9	30,0	25,4
	JF5	0,081	0,042	1,105	0,2890	2614,8	15,2	13,9	31,0	26,4
	JF6	0,084	0,042	1,141	0,3090	2711,6	15,8	14,5	30,0	25,4
	JF7	0,083	0,042	1,125	0,2950	2621,9	15,3	14,0	30,0	25,4

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NB: Correction times for pulsing heads:
P-Wave - 1,3 μsec
S-Wave - 4,6 μsec

where T_p = travel time for P-wave
 T_s = travel time for S-wave

Table B3 Transmission of body waves through Andesite rock specimens

MATERIAL	SPECIMEN NUMBER	LENGTH m	DIAMETER m	VOLUME m ³ x10 ⁻⁴	MASS kg	DENSITY kg/m ³	TRANSMISSION TIMES			
							T _p		T _s	
							Measured μs	Corrected μs	Measured μs	Corrected μs
ANDESITE	X1	0,098	0,040	1,253			15,6	14,3	29,0	24,4
	X2	0,094	0,040	1,181			15,2	13,9	28,5	23,9
	X3	0,145	0,041	1,862			23,3	22,0	45,5	40,9
	X4	0,065	0,040	0,828			11,6	10,3	25,0	20,4
	AA1	0,084	0,041	1,092	0,3129	2864,6	13,4	12,1	26,5	21,9
	AA2	0,032	0,041	1,071	0,3072	2867,3	13,2	11,9	26,5	21,9
	AA3	0,082	0,041	1,073	0,3075	2865,2	13,2	11,9	27,0	22,4
	AA4	0,082	0,041	1,073	0,3105	2893,5	13,4	12,1	27,5	22,9

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NB:

The length is the average of three measurements

The diameter is the average of four measurements

The mass was measured to 0,1g

Correction times for pulsing heads:

P-Wave - 1,3 μsec

S-Wave - 4,6 μsec

X1, X2, X3 and X4 were
different length andesite
cores used to determine
the correction times for
the pulsing heads

where:

T_p = travel time for P-waveT_s = travel time for S-Wave

Table B3 Transmission of body waves through Andesite rock specimens /continued

MATERIAL	SPECIMEN NUMBER	LENGTH m	DIAMETER m	VOLUME $\times 10^{-4}$ m^3	MASS kg	DENSITY kg/m^3	TRANSMISSION TIMES			
							T_p		T_s	
							Measured μs	Corrected μs	Measured μs	Corrected μs
ANDESITE	AA5	0,082	0,041	1,067	0,3061	2867,7	13,3	12,0	27,0	22,4
	AA6	0,082	0,040	1,050	0,3017	2874,2	13,2	11,9	27,0	22,4
	AA7	0,082	0,040	1,054	0,3016	2860,5	13,2	11,9	26,5	21,9
	AB1	0,082	0,040	1,030	0,2962	2874,8	13,2	11,9	26,5	21,9
	AB2	0,084	0,041	1,099	0,3170	2884,8	13,6	12,3	26,5	21,9
	AB3	0,084	0,040	1,081	0,3117	2883,7	13,6	12,3	26,5	21,9
	AB4	0,084	0,039	1,011	0,2874	2843,6	13,4	12,1	26,0	21,4
	AB5	0,084	0,041	1,099	0,3152	2867,8	13,5	12,2	26,5	21,9

NB:

The length is the average of three measurements
 The diameter is the average of four measurements
 The mass was measured to 0,1g
 Correction times for pulsing heads:
 P-Wave - 1,3 μsec
 S-Wave - 4,6 μsec

where T_p = travel time for P-wave
 T_s = travel time for S-wave

Table B3 Transmission of body waves through Andesite rock specimens /continued

MATERIAL	SPECIMEN NUMBER	LENGTH m	DIAMETER m	VOLUME $\times 10^{-4}$ m^3	MASS kg	DENSITY kg/m^3	TRANSMISSION TIMES			
							T_p		T_s	
							Measured μs	Corrected μs	Measured μs	Corrected μs
ANDESITE	AB6	0,083	0,041	1,084	0,3116	2875,5	13,2	11,9	26,2	21,6
	AB7	0,084	0,041	1,081	0,3141	2905,6	13,2	11,9	26,2	21,6
	AC1	0,084	0,041	1,092	0,3145	2878,8	13,6	12,3	27,0	22,4
	AC2	0,084	0,041	1,093	0,3144	2876,7	13,6	12,3	26,5	21,9
	AC3	0,084	0,041	1,093	0,3144	2876,8	13,6	12,3	27,2	22,6
	AC4	0,084	0,041	1,096	0,3150	2873,9	13,5	12,2	27,0	22,4
	AC5	0,084	0,041	1,096	0,3151	2873,4	13,6	12,3	27,2	22,6
	AC6	0,084	0,041	1,095	0,3154	2880,7	13,6	12,3	27,0	22,4
	AC7	0,084	0,041	1,095	0,3147	2873,1	13,6	12,3	27,8	23,2

NB:

The length is the average of three measurements
 The diameter is the average of four measurements
 The mass was measured to 0,1g
 Correction times for pulsing heads:

P-Wave - 1,3 μsec S-Wave - 4,6 μsec

where T_p = travel time for P-wave
 T_s = travel time for S-wave

APPENDIX C

STATIC MODULUS TEST PROCEDURE AND RESULTS FOR CONCRETES

Static Modulus Test for Concrete, Paste and Mortar

The following procedure was adhered to for concretes, pastes and mortars. The test was similar to BS 1981: PART 121: 1983¹.

Apparatus

The static modulus apparatus is shown in Figure C1 and consists of the following.

- a) Static test rig with adjusting screws and calibrated LVDTs (linear variable differential transformers).
- b) XY recorder measuring longitudinal and lateral displacements.
- c) Power pack capable of supplying a constant 6V output. Before each test the output of the power pack was checked by the use of an accurate digital voltmeter.
- d) A digital voltmeter capable of measuring one tenth of a millivolt.
- e) A compression loading machine (Tinius Olsen).
- f) A stopwatch and a ruler.

Procedure

End faces of specimens were ground before test to ensure a plane loading surface. The prisms were marked with centre lines and

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gauge length lines for their respective static rigs. This facilitated the fixing of the rig and ensured that the extension was measured over the correct gauge length. The static rig was adjusted to ensure the LVDTs were perpendicular to the fine adjusting screws. Figure C2 shows a paste specimen held in the static paste/mortar rig. The prism was mounted in a Tinius Olsen loading machine and connected to an XY recorder.

The specimen was carefully centred in the loading machine and the loading platen levelled to ensure concentric loading. A pre-load as given in table C1 was applied to the specimen and held constant for approximately one minute. During this time a voltmeter was connected across the outputs of the longitudinal and lateral LVDTs, which were then zeroed by means of the fine adjusting screws. This ensured that the movement of the cores of the LVDT was in its linear range. The XY plotter was set at suitable sensitivities and the longitudinal and lateral pens positioned at a convenient origin, usually the top left hand corner of the XY chart.

In accordance with BS 1881: PART 121: 1983 the load was increased at a rate of 15 MPa/min up to a value of one third of the mean compressive strength. The theoretical compressive strength, f_c , (which was based on concrete cube strengths) was computed from c/w ratio and design charts. Table C1 gives the various values used for the concretes, mortars and pastes. The load was applied at this rate up to the value of one third of the compressive strength. This load was maintained for one minute. Then the specimen was unloaded at 15 MPa/min to the pre-load value which was maintained for one minute. The XY pens were re-zeroed and the procedure repeated twice. The elastic modulus was determined from the third trace. The XY recorder sensitivity was then reduced and the specimen reloaded at the prescribed rate to failure.

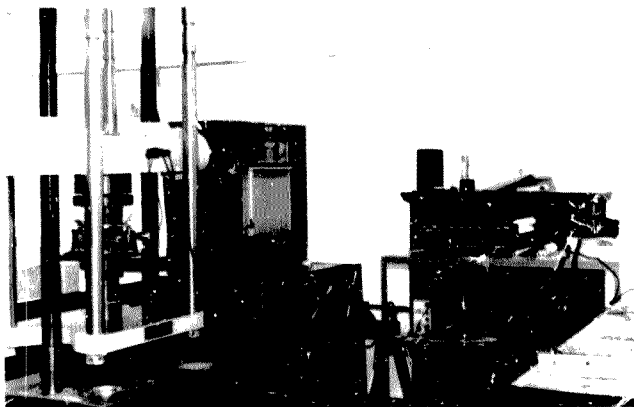


Figure C1 Static Modulus Testing Apparatus for Pastes, Mortars and Concrete

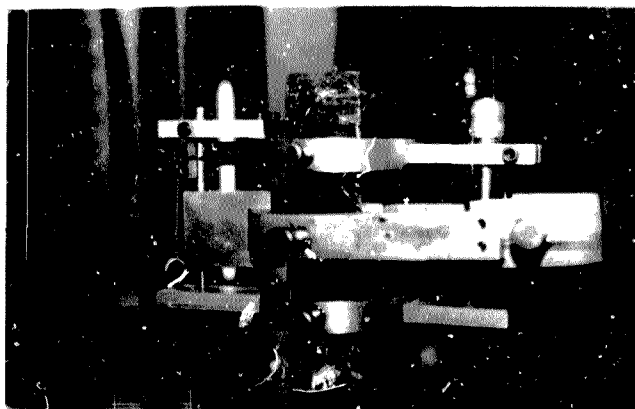


Figure C2 Paste Specimen held in Static Testing Rig

APPENDIX C

Calculation of Results

Figure C3 shows a typical trace for an andesite concrete, cement/water ratio 1,5 and 700 kg/m³ stone content. From the final plot, plot 3, slope AA¹ was taken to determine the static elastic modulus. Due to the static rig "bedding in" an approximately horizontal portion was evident on both the longitudinal and lateral stress/strain plots. Slope AA¹ and BB¹ were constructed parallel to their respective curves, extrapolated back to give correction distances and the true origin of each curve. The slopes were converted to an elastic modulus E value and Poisson's ratio value, by previously ascertained calibrations incorporating LVDTs, loading machine and the XY plotter.

Tables C2 and C3 give static elastic modulus results for granite and andesite concretes respectively.

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Table C1 Pre-loads, Loading Rate, 'E' Load Values and Loading
Machine Settings for Concretes, Pastes and Mortars

SPECIMEN	C/W RATIO	PRE- LOAD	LOADING RATE (15MPa/min)	PREDICTED COMPRESSIVE STRENGTH f_c MPa	'E' LOAD ($f_c/3 \times \text{AREA}$) kN
		kN	kN/min		
CONCRETE 101.6x101.6 x250 mm	1,5	5,0	155	28,0	96,3
	1,8	5,0	155	36,5	125,9
	2,4	5,0	155	52,0	178,9
PASTE AND MORTARS 40x40x160mm	1,5	0,8	24	28,0	14,9
	1,8	0,8	24	36,5	19,5
	2,1	0,8	24	44,3	23,6
	2,4	0,8	24	52,0	27,7

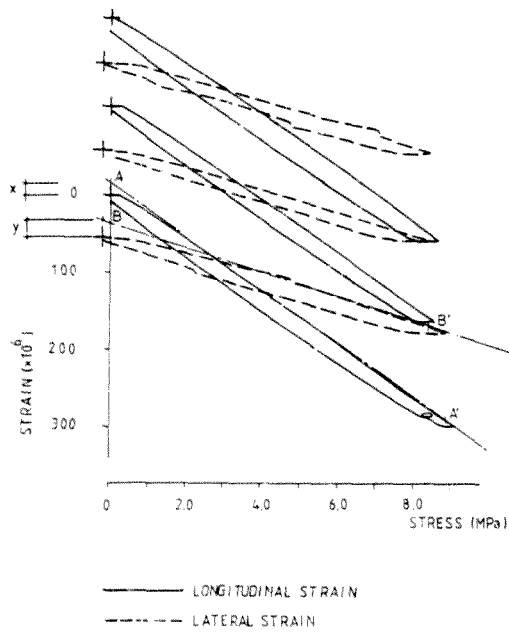


Figure C3 Typical Trane for Concrete showing Slopes taken for Determination of E and ν Values

Table C2 Static Modulus Results for Granite Concrete

SPECIMEN		LOAD AT FAILURE kN	STRESS AT FAILURE MPa	E_c GPa	ν	MODE OF FAILURE
700 kg/m ³ c/w = 1,5	1	222,6	20,98	22,54	0,17	C
	2	218,0	20,57	23,67	0,17	B
	3	212,4	20,02	23,65	0,17	B
	4	216,6	20,43	23,96	0,16	B
700 kg/m ³ c/w = 1,8	1	262,0	24,69	29,72	0,18	B
	2	284,5	26,84	32,22	0,19	A
	3	229,8	21,66	31,16	0,18	B
	4	316,8	29,89	26,63	0,18	B
700 kg/m ³ c/w = 2,4	1	408,3	38,77	30,18	0,21	B
	2	402,9	38,08	29,53	0,22	B
	3	399,2	37,91	29,80	0,21	B
	4	399,8	37,78	29,60	0,19	B

Table C2 Static Modulus Results for Granite Concrete (continued)

SPECIMEN		LOAD AT FAILURE kN	STRESS AT FAILURE MPa	E _c GPa	ν	MODE OF FAILURE
1000 kg/m ³ c/w = 1,5	1	187,0	17,81	24,53	0,14	C
	2	220,8	21,45	25,23	0,16	C
	3	182,2	17,35	25,76	0,16	A & C
	4	214,0	20,79	20,45	0,18	B
1000 kg/m ³ c/w = 1,8	1	290,8	27,23	30,28	0,12	B & C
	2	283,6	26,62	24,12	0,13	C
	3	279,0	26,13	29,12	0,16	A
	4	265,7	24,94	27,26	0,18	C
1000 kg/m ³ c/w = 2,4	1	377,0	35,49	32,05	0,19	C
	2	339,4	32,07	29,69	0,20	C
	3	374,9	35,30	31,90	0,22	C & B
	4	382,5	36,15	31,83	0,20	B

Table C2 Static Modulus Results for Granite Concrete (continued)

SPECIMEN		LOAD AT FAILURE kN	STRESS AT FAILURE MPa	E_c GPa	ν	MODE OF FAILURE
1300 kg/m ³ c/w = 1,5	1	167,9	15,75	26,97	0,19	B
	2	175,9	15,65	24,32	0,15	B & C
	3	175,5	16,46	25,04	0,16	B & C
	4	178,0	16,70	23,18	0,14	B
1300 kg/m ³ c/w = 1,6	1	247,9	23,42	29,54	0,17	B
	2	263,6	24,88	28,15	0,16	B
	3	253,0	23,91	30,34	0,16	A & B
	4	286,1	27,00	29,17	0,17	B
1300 kg/m ³ c/w = 2,4	1	383,4	36,31	33,23	0,20	B
	2	404,3	37,71	31,94	0,16	B
	3	346,5	32,82	31,76	0,20	B
	4	347,4	32,41	36,03	0,23	B

Table C3

Static Elastic Modulus Results for Andesite
Concrete

SPECIMEN	LOAD AT FAILURE kN	STRESS AT FAILURE MPa	E_c GPa	FAILURE TYPE	
700 kg/m ³					
c/w = 1,5					
1	225,2	21,29	29,25	0,18	A
2	239,6	23,01	33,61	0,20	B
3	273,2	25,84	28,55	0,19	B
4	248,4	23,86	31,81	0,21	
c/w = 1,8					
1	277,9	26,23	31,79	0,20	
2	338,7	31,70	31,98	0,17	
3	308,2	29,09	33,26	0,20	
4	313,2	29,32	34,67	0,22	
c/w = 2,4					
1	404,1	37,73	36,57	0,23	
2	377,8	35,98	36,49	0,18	
3	444,3	41,48	35,27	0,20	
4	421,4	40,14	36,50	0,21	

Table C3 Static Elastic Modulus Results for Andesite
Concrete /continued

SPECIMEN	LOAD AT FAILURE kN	STRESS AT FAILURE MPa	E_c GPa	FAILURE TYPE	
1000 kg/m ³ c/w = 1,5					
1	217,3	20,43	31,26	0,19	A
2	219,0	20,49	35,14	0,21	B
3	251,0	23,60	34,59	0,20	C
4	226,3	21,17	36,99	0,21	B
c/w = 1,8					
1	286,8	26,80	37,71	0,20	A
2	356,3	33,71	37,71	0,20	A
3	292,6	27,35	38,53	0,21	B
4	317,8	30,07	35,97	0,20	A
c/w = 2,4					
1	371,3	34,62	40,44	0,18	B
2	373,8	35,06	39,89	0,22	B
3	399,6	37,26	42,65	0,25	B
4	355,4	33,34	39,42	0,22	B

Table C3 Static Elastic Modulus Results for Andesite
Concrete /continued

SPECIMEN	LOAD AT FAILURE kN	STRESS AT FAILURE MPa	E_c GPa	FAILURE TYPE
1300 kg/m ³				
c/w = 1,5				
1	237,2	22,18	38,95	0,19
2	199,5	18,65	40,18	0,21
3	226,0	21,13	42,10	0,22
4	204,0	19,07	37,40	0,19
c/w = 1,8				
1	297,8	27,83	44,03	0,23
2	275,0	25,85	40,06	0,20
3	279,3	26,10	44,20	0,22
4	284,3	26,72	41,43	0,21
c/w = 2,4				
1	361,8	34,20	44,54	0,24
2	358,8	33,68	41,87	0,18
3	384,9	36,38	44,84	0,20
4	384,6	36,10	46,15	0,21

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1. BRITISH STANDARD Testing Concrete Part 121 Method for
Determination of Static Modulus of Elasticity in
Compression BS 1881: PART 121: 1983

APPENDIX D

APPARATUS DESIGNED FOR PROJECT

D1 Paste/Mortar Moulds and Rotating Hardening/Setting Device

Since cement pastes tend to segregate if conventional casting methods are used, an approach similar to that of Spooner¹ was adopted. Finely machined, sealed moulds were designed and manufactured. The moulds were sealed by the use of petroleum jelly. Figure 2.9(a) in chapter 2 shows a partially dismantled mould. A rotating machine for up to six moulds was also designed. The machine was designed to rotate the moulds at six revolutions per minute. The sealed moulds on the rotating machine are shown in figure 2.9(b) of chapter 2. This technique helped reduce segregation in the pastes and mortars and ensure better uniformity of specimens. The steel moulds were all covered with an oil releasing agent and clamped together by Allen screws. The joints were sealed by petroleum jelly.

D2 Electrodynamic Apparatus for Concrete, Pastes and Mortars

The electrodynamic apparatus is shown in figure E2 of appendix E. A full description of the apparatus and the technique used is also given in appendix E. All of this apparatus was made up to enable the dynamic electrodynamic modulus to be determined in accordance with BS 1881².

APPENDIX D

D3 Static Modulus Testing Apparatus for Pastes, Mortars
and Concrete

A full description of the apparatus and procedure is given in appendix C. It was decided to use LVDT's (linear variable differential transformers) to measure deformations of specimens. Therefore, lightweight aluminium rigs were designed for both paste, mortar and concrete specimens. The rigs held the LVDT's in required position to determine longitudinal and transverse deformations of specimens under load. The rigs were calibrated against a strain gauged steel cylinder. Accurate E-values were determined for the pastes, mortars and concretes using calibration factors determined for the LVDT's, the Tinius Olsen and the X-Y plotter.

APPENDIX D

REFERENCES

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ELECTRODYNAMIC ELASTIC MODULUS LABORATORY PROCEDURE AND
RESULTS FOR PASTES, MORTARS AND CONCRETES

Electrodynamic Test for Modulus of Elasticity

The most convenient way of measuring the modulus of elasticity of concrete is by vibrational techniques¹. Resonance techniques were first used about thirty years ago² and have become part of concrete testing technology. The concrete has to be in a well defined shape to allow resonance in some particular mode to be excited by a vibrator. At a particular resonant frequency the dynamic modulus of elasticity can be estimated. The most common specimen employed in resonance tests is a beam of rectangular or square cross-section, which is also often used in flexural strength measurements. The British Standard³ (BS 1881) gives details of the method employed to excite the fundamental longitudinal resonance of square section standard beams. The electrodynamic apparatus used in the project was modelled on the aforementioned method. Calculation of dynamic moduli were performed in accordance with BS 1881 for pastes, mortars and concretes

In some cases it is desirable to determine progressive changes in the strength and stiffness of a concrete, mortar or paste specimen. For example it might be necessary to determine concrete deterioration due to damaging action of frost or chemical attack. Resonance methods are specified in the United States of America as a means of determining resistance to frost, and they have been used in other countries to determine resistance to attack by sulphate or sea water. Being non-destructive the methods have considerable advantages over conventional strength and stiffness methods. Repetitive tests to study ageing and durability can be made on the same specimen, so considerable economy is effected in the number of specimens required. The chief disadvantage of resonance methods is that they are restricted to specimens of

APPENDIX E

shapes for which it is possible to derive the frequency equation¹. Martincek⁴ has recently computed results for the resonant frequencies of cubes and discs, to enlarge the range of specimen shapes to which the technique can be applied. Resonance techniques are rarely applicable to in situ structural concrete and pulse propagation methods are more suitable for in situ testing¹.

Using the arrangement shown in figure E1 Kaplan⁵ found an increase in path length (i.e. the length of specimen) gave greater accuracy in calculations. The ASTM standard C215-60⁶ describes the measurement of longitudinal resonant frequency, transverse (flexural) frequency and torsional frequency. The schematic layout of this apparatus is shown in figure E1.

The dynamic elastic modulus determined in this way is usually considerably higher than the static modulus of elasticity. Negligible stress is applied to the specimen during vibration; hence the dynamic modulus refers to almost purely elastic effects and it is unaffected by creep⁶. Kaplan⁵ also concluded from his investigations on thirteen different types of coarse aggregate that changes with age in the dynamic modulus were chiefly due to changes in the mortar phase of the concrete. The type of aggregate and mix proportions affect the dynamic modulus. He found a highly significant correlation between dynamic modulus and the flexural or compressive strength. These relationships are affected by the type of aggregate and the mix proportions.

Apparatus

The apparatus is shown in figure E2.

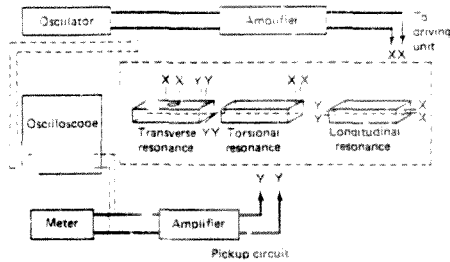


Figure E1 Schematic Diagram of Typical Apparatus showing Driver and Pick Up Positions for Three Types of Vibration (After ASTM C215)

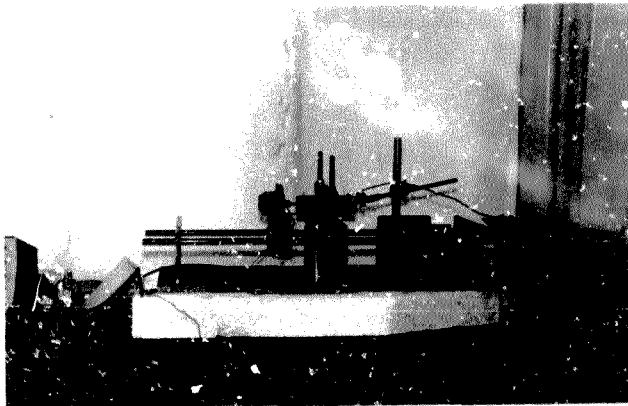


Figure E2 Electrodynamic Apparatus for Concretes, Pastes and Mortars

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The apparatus consisted of the following

- a) a variable frequency oscillator with a range of zero to 20 kHz. Output power variable to 2kW.
- b) an electromagnetic exciter unit of which the part to be attached to the beam had a mass not greater than 0,2% of the mass of the specimen.
- c) The vibration stylus pick up also had no resonances at frequencies below 10 kHz.
- d) a cathode ray oscilloscope
- e) a frequency counter
- f) an audio frequency amplifier
- g) a fixed clamp with a maximum width of 1/20 the length of the specimen
- h) a thick polystyrene base to form an anti-vibrational mounting
- i) a balance of adequate capacity and accuracy of 10g

Procedure

The beams were removed from the curing tank and tested while still wet. Surface water and grit were wiped off the beam before it was clamped in position. The ends of each specimen were also ground plane unless they had been cast against a machined steel mould. The electromagnetic exciter unit was adjusted until it was

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touching the specimen centrally. The stylus pick up was adjusted and fixed centrally on the other end of the specimen by means of a magnetic clamp. The variable frequency oscillator was switched on and the frequency varied until a peak output was observed on the oscilloscope. The frequency was then read off the frequency counter. This procedure was carried out three times to obtain a mean resonant frequency. Care was taken during this operation to ensure that the peak trace on the oscilloscope was not a harmonic.

The following additional measurements were also made on each specimen:-

- i) The weight, W_a , in kilogrammes of the wet specimen in air.
- ii) The length, λ , in millimetres of the specimen using the mean of four symmetrically placed measurements.
- iii) The density, ρ , in kilogrammes per cubic metre by determining the average width, b , and depth, d , in millimetres from six equally spaced measurements along the length of the specimen.

$$\text{Then } \rho = \frac{W_a}{\lambda b d} \times 10^9 \text{ (kg/m}^3\text{)} \quad \dots\dots (E.1)$$

Nominal specimen size for concrete was 100mm x 100mm x 500mm
and for the mortars and pastes 40mm x 40mm x 160mm.

Calculation

The dynamic modulus, E_d , of each specimen was calculated from

$$E_d = 4 \pi^2 f^2 \rho \cdot 10^{-9} \text{ GPa} \quad \dots\dots (E.2)$$

APPENDIX E

where:

- l = length of the specimen in millimetres
- n = natural frequency of the fundamental mode of longitudinal vibration of the specimen in hertz and
- ρ = density in kilogrammes per cubic metre

Tables of Results

The results of the above calculations are given in tables E1 for pastes, tables E2(a) and E2(b) for granite and andesite mortars respectively and tables E3(a) and E3(b) for granite and andesite concretes respectively.

Table E1 Electrodynamic Elastic Modulus Results for Pastes

C/W RATIO	SPECIMEN NUMBER	WEIGHT kg	LENGTH l (mm)	BREADTH b (mm)	DEPTH d (mm)	DENSITY $\rho \text{ kg m}^{-3}$	ELECTRO- DYNAMIC n kHz	DYNAMIC MODULUS GPa
1,5	1	0,436	160,11	39,67	40,05		6,64	7,75
	2	0,434	160,48	39,76	40,28		6,65	7,69
	3	0,454	160,53	39,84	40,24	1764,10	6,60	7,92
	4	0,435	160,15	39,72	40,11	1704,91	6,70	7,85
1,8	1	0,470	160,70	39,82	40,23	1825,71	13,50	*34,37
	2	0,462	160,43	40,25	39,61	1806,34	16,14	*48,44
	3	0,462	160,25	39,77	40,12	1806,87	7,60	10,72
	4	0,466	160,23	40,22	40,08	1804,15	7,40	10,15

* The above two results are neglected when averaging the electrodynamic modulus. Obviously the frequency measured was a higher harmonic and not the fundamental frequency of the specimen.

Table E1 Electrodynamic Elastic Modulus Results for Pastes /continued

C/W RATIO	SPECIMEN NUMBER	WEIGHT W_p kg	LENGTH l (mm)	BREADTH b (mm)	DEPTH d (mm)	DENSITY ρ kg/m ³	ELECTRO- DYNAMIC η kHz	DYNAMIC MODULUS GPa
2,1	1	0,506	160,37	40,39	39,78	1963,76	9,34	17,62
	2	0,492	160,73	39,60	39,38	1962,90	8,88	15,99
	3	0,501	160,45	39,55	40,29	1939,92	9,27	17,17
	4	0,504	160,71	39,78	40,20	1961,09	9,08	16,70
	5	0,505	160,48	39,77	40,33	1961,94	8,81	15,69
2,4	1	0,511	160,25	39,82	40,23	1990,54	9,25	17,49
	2	0,511	160,35	39,87	40,38	1979,43	9,49	18,33
	3	0,512	160,53	39,70	40,33	1992,03	9,14	17,15
	4	0,515	160,25	40,07	40,27	1991,63	9,41	18,12
	5	0,502	160,47	39,60	40,13	1968,55	8,69	15,31

Table E2(a) Electrodynamic Elastic Modulus Results for Granite Mortars

C/W RATIO	SPECIMEN NUMBER	WEIGHT W_a kg	LENGTH l (mm)	BREADTH b (mm)	DEPTH d (mm)	DENSITY ρ kg/m ³	ELECTRO- DYNAMIC n kHz	DYNAMIC MODULUS GPa
1,5	1	0,524	154,35	38,61	39,58	2221,51	10,48	23,26
	2	0,533	155,35	39,78	38,63	2232,68	10,30	22,88
	3	0,535	154,03	40,02	38,79	2237,44	12,06	30,88
	4	0,520	153,55	39,73	38,57	2209,96	11,53	27,72
1,8	1	0,534	151,95	38,86	39,85	2269,39	12,06	30,48
	2	0,542	151,58	38,94	39,88	2302,54	12,58	33,51
	3	0,535	155,10	38,65	39,85	2239,57	12,58	34,13
	4	0,537	154,79	38,73	39,88	2246,24	11,53	28,63

Table E2(a) Electrodynamic Elastic Modulus Results for Granite Mortars /continued

c/w RATIO	SPECIMEN NUMBER	WEIGHT W_a kg	LENGTH l (mm)	BREADTH b (mm)	DEPTH d (mm)	DENSITY ρ kg/m ³	ELECTRO- DYNAMIC n kHz	DYNAMIC MODULUS GPa
2,4	1	0,538	150,05	39,59	38,99	2322,78	13,14	36,14
	2	0,554	153,00	40,08	38,90	2322,42	13,32	38,58
	3	0,544	152,95	39,62	38,86	2310,11	12,65	34,61
	4	0,547	150,85	38,84	39,87	2341,62	12,72	34,51

Table E2(b) Electrodynamic Elastic Modulus Results for Andesite Mortars

C/W RATIO	SPECIMEN NUMBER	WEIGHT W_a kg	LENGTH l (mm)	BREADTH b (mm)	DEPTH d (mm)	DENSITY ρ kg/m ³	ELECTRO- DYNAMIC MODULUS n kHz	DYNAMIC MODULUS GPa
1.5	1	0.562	153.10	38.75	40.00	2368.26	12.58	35.16
	2	0.551	151.29	38.79	39.67	2366.79	12.06	31.51
	3	0.554	153.60	38.52	39.67	2360.32	11.53	29.63
	4	0.546	151.40	39.76	38.48	2357.14	12.06	31.43
1.8	1	0.573	154.55	36.79	39.95	2392.48	12.06	33.24
	2	0.569	152.96	39.90	33.79	2405.06	12.58	35.60
	3	0.571	155.10	39.73	38.97	2377.80	12.48	35.63
	4	0.561	152.1	39.85	38.76	2383.39	12.58	35.06

Table E2(b) Electrodynamic Elastic Modulus Its for Andesite Mortars /continued

C/W RATIO	SPECIMEN NUMBER	WEIGHT W_a kg	LENGTH l (mm)	BREADTH b (mm)	DEPTH d (mm)	DENSITY ρ kg/m ³	ELECTRO- DYNAMIC MODULUS n kHz	DYNAMIC MODULUS GPa
2,4	1	0,559	153,40	39,83	38,57	2372,06	12,58	35,36
	2	0,564	152,86	38,77	40,05	2376,22	12,76	36,16
	3	0,570	153,46	38,43	39,81	2427,82	12,79	37,44
	4	0,561	153,42	38,81	39,53	2383,47	12,58	35,54

Table E3(a) Electrodynamic Elastic Modulus Results for Granite Concretes

STO.IE CONTENT kg/m ³	C/W RATIO	SPECIMEN NUMBER	WEIGHT W _a kg	LENGTH l (mm)	BREADTH b (mm)	DEPTH d (mm)	DENSITY ρ kg/m ³	NATURAL FREQUENCY n kHz	DYNAMIC MODULUS GPa
700	1.5	1	12,24	493	102,56	103,5	2338,14	3,91	34,81
		2	12,12	489	103,17	102,74	2338,30	3,86	33,34
700	1.8	1	12,16	492	103,08	102,68	2335,11	3,55	28,42
		2	12,16	495	101,02	102,64	2369,21	3,49	28,33
700	2.4	1	12,35	494	102,49	102,74	2370,36	3,65	30,83
		2	12,32	491	103,14	102,65	2369,97	3,65	30,46
1000	1.5	1	12,24	493	102,45	102,49	2364,51	3,55	28,90
		2	12,00	494	102,73	100,19	2362,48	3,55	28,93
1000	1.8	1	12,52	493	102,98	103,70	2378,08	3,65	30,81
		2	12,45	494	102,82	103,63	2366,46	4,18	40,24

Table E3(a) Electrodynamic Elastic Modulus Results for Granite Concretes /continued

STONE CONTENT kg/m ³	c/w RATIO	SPECIMEN NUMBER	WEIGHT W _a kg	LENGTH l (mm)	BREADTH b (mm)	DEPTH d (mm)	DENSITY ρ kg/m ³	NATURAL FREQUENCY n kHz	DYNAMIC MODULUS GPa
1000	2,4	1	12,58	492	102,67	103,45	2406,52	3,76	32,90
		2	12,51	490	102,45	103,29	2412,44	3,76	32,68
1300	1,5	1	12,75	495	104,11	102,40	2415,14	3,65	31,54
		2	12,54	492	102,62	102,96	2413,34	3,55	29,34
1300	1,8	1	12,66	494	102,78	102,97	2399,59	3,13	22,85
		2	12,72	496	103,10	102,76	2421,33	3,65	31,69
1300	2,4	1	12,75	497	102,30	103,20	2430,15	3,81	34,82
		2	12,93	494	102,54	104,55	2440,72	3,86	35,51

Table E3(b) Electrodynamic Elastic Modulus Results for Andesite Concretes

STONE CONTENT kg/m ³	C/W RATIO	SPECIMEN NUMBER	WEIGHT W _a kg	LENGTH l (mm)	BREADTH b (mm)	DEPTH d (mm)	DENSITY ρ kg/m ³	NATURAL FREQUENCY n kHz	DYNAMIC MODULUS GPa
700	1,5	1	12,87	487	102,63	103,04	2498,63	3,60	30,69
		2	13,01	496	101,45	102,63	2519,63	3,60	32,10
700	1,8	1	12,98	491	103,02	102,84	2494,15	3,13	23,51
		2	13,09	493	104,05	102,68	2487,36	2,91	20,50
700	2,4	1	13,17	492	103,33	103,67	2500,83	3,86	36,02
		2	13,07	491	102,48	102,46	2533,43	3,76	34,50
1000	1,5	1	13,47	500	103,49	102,79	2531,74	3,64	33,54
		2	13,40	489	104,35	102,42	2564,20	3,76	34,59
1000	1,8	1	13,55	496	103,78	103,11	2552,77	3,76	35,43
		2	13,48	493	102,89	102,72	2584,05	3,70	34,50

Table E3(b) Electrodynamic Elastic Modulus Results for Andesite Concretes /continued

STONE CONTENT kg/m^3	C/W RATIO	SPECIMEN NUMBER	WEIGHT W_a kg	LENGTH l (mm)	BREADTH b (mm)	DEPTH d (mm)	DENSITY ρ kg/m^3	NATURAL FREQUENCY n kHz	DYNAMIC MODULUS GPa
1000	2.4	1	13.56	492	102.43	104.71	2567.43	3.97	39.14
		2	13.55	495	103.76	102.75	2567.38	4.02	40.63
1300	1.5	1	13.68	495	102.68	104.16	2583.82	3.81	36.72
		2	13.60	497	103.31	103.56	2559.33	3.81	36.60
1500	1.8	1	13.76	498	104.40	102.49	2583.79	3.91	39.21
		2	13.42	490	103.25	103.04	2572.04	3.91	37.87
1800	2.4	1	13.84	497	102.83	102.88	2632.64	3.97	40.91
		2	13.75	493	103.76	102.68	2616.68	4.07	42.20

APPENDIX E

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APPENDIX F

ULTRASONIC METHOD FOR PASTE, MORTAR AND CONCRETE

This form of testing employs pulses in the frequency range of 50-150 per second, generated and recorded by electronic circuits. The commercial equipment available is robust, lightweight equipment suitable for site as well as laboratory use.

Theory of Pulse Propagation through Concrete

Three types of wave are generated by an impulse applied to a solid mass.

- i) Surface waves having an elliptical particle displacement are the slowest.
- ii) Shear or transverse waves with particle displacement at right angles to the direction of travel are faster.
- iii) Longitudinal waves with particle displacement in the direction of travel (compression waves) are the most important since these are the fastest and provide more useful information.

The wave velocities depend on the elastic properties and density of the medium and hence if the density and velocity of wave propagation are known, it is possible to assess the elastic properties. For an infinite, homogeneous isotropic elastic medium the compression wave velocity is given by:

$$V = \frac{(K + \frac{4}{3}G)}{\rho}^{1/2} \quad \dots (F.1)$$

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where V = compressional wave velocity (km/sec)

$$K = \frac{(1 - \nu)}{(1 - \nu)(1 - 2\nu)} \quad \dots (F.2)$$

E_d = dynamic modulus of elasticity (GPa)

ρ = density (kg/m^3)

ν = dynamic Poisson's ratio

K is relatively insensitive to variations in dynamic Poisson's ratio and hence provided that a reasonable estimate of this value and the density can be made, it is possible to compute E_d using a measured value of wave velocity V . Since ρ and ν vary little for mixes containing natural aggregates (in the case of concrete), the relationship between velocity and dynamic elastic modulus may be expected to be reasonably constant despite the fact that concrete is not an 'ideal' medium to which the above equation applies¹.

Equipment and Use

The basic circuitry requirements are shown in Figure F1. Basically the test equipment must provide a means of generating a pulse, transmitting this to the concrete mortar or paste, receiving and amplifying the pulse and measuring and displaying the transit time. Repetitive voltage pulses are generated electronically and transformed into wave bursts of mechanical energy by the transmitting transducer, which must be coupled to the concrete surface through a suitable medium. A similar receiving transducer is also coupled to the concrete at a known distance from the emitter and the mechanical energy converted back to electrical pulses of the same frequency. The electronic timing device measures the interval between onset and reception of the

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pulse and this is displayed on a digital readout. For concrete, testing transducers with natural frequencies between 20 kHz and 150 kHz are most suitable.

Apparatus

The apparatus is shown in figure F2. The apparatus consisted of:-

- a) An ultrasonic tester (a Steinkamp ultrasonic tester type BP1V), with exciting and receiving transducers, natural frequency 40 kHz.
- b) A standard calibration bar.
- c) Coupling medium, petroleum jelly.

Procedure

The ultrasonic tester was calibrated using the standard 10 μ s calibration bar. The specimens were removed from the curing tank and surface water and grit was cleaned off. Special care was taken to ensure the ends of the specimens were clean and surface dry to ensure good acoustical coupling between the specimen surface and the face of the transducer. Petroleum jelly was applied to the ends of the transducers and attached to the specimen. All air pockets were eliminated as far as possible and only a thin separating layer, any surplus being squeezed out by pressure. If the specimen was rough or uneven it was ground to provide a smooth surface for transducer application. The readings were repeated three times for each specimen, using the direct method of transmission. The various types of readings are shown in figure F3. The direct method is the most reliable from the point of view of transit time measurement.

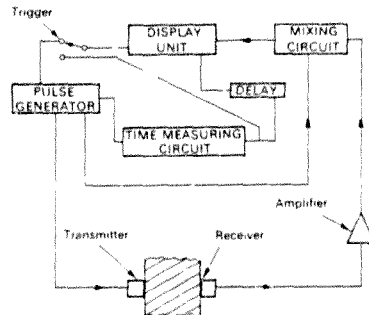


Figure F1 Typical Ultrasonic Pulse Velocity Testing Equipment
(After Bungey¹)

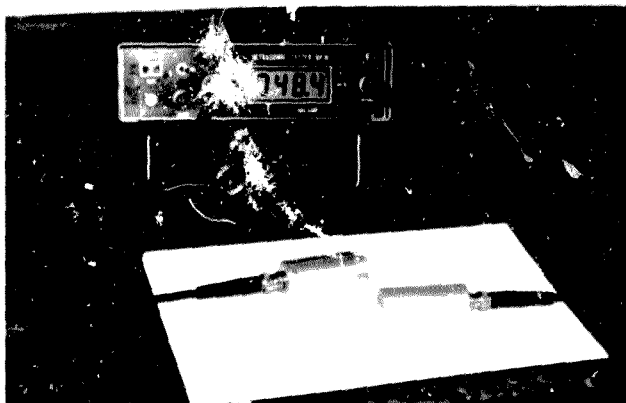


Figure F2 Ultrasonic Testing Equipment

APPENDIX F

Additional measurements of mass, length and density were performed as described in Appendix E for electrodynamic modulus of elasticity.

Calculation

As previously stated, the ultrasonic dynamic modulus of elasticity can be calculated from the knowledge of the density and pulse velocity. The dynamic modulus of elasticity is given by²

$$E_d = \rho V^2$$

for specimens with lateral dimension less than one wavelength where:

E_d is the ultrasonic dynamic modulus of elasticity GPa

ρ is the density kilograms per cubic metre

V is the transmission time metres per second.

The results of the above calculations are given in table F1 for pastes, table F2(a) and F2(b) for granite and andesite mortars respectively and F3(a) and F3(b) for granite and andesite concretes respectively.

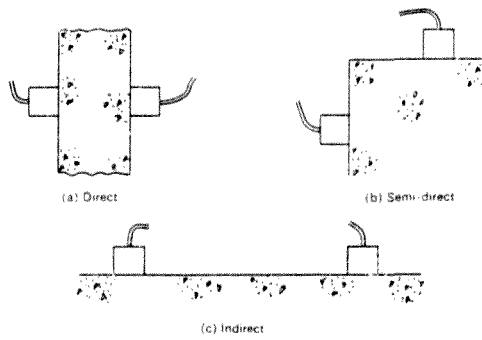


Figure F3 Types of Reading (After Bungey¹)

Table F1 Ultrasonic Dynamic Elastic Modulus for Pastes

RATIO	SPECIMEN NUMBER	ULTRASONIC TRAVEL TIME T μ s	ULTRASONIC VELOCITY V ms^{-1}	ULTRASONIC DYNAMIC MODULUS GPa
1,5	1	56,7	2823,8	13,67
	2	57,6	2786,1	13,11
	3	57,1	2811,4	13,94
	4	60,7	2638,4	11,87
1,8	1	52,2	3078,5	17,30
	2	52,0	3085,1	17,19
	3	53,5	2995,3	16,21
	4	51,8	3093,2	17,26
2,1	1	45,7	3509,2	24,18
	2	47,8	3362,6	22,19
	3	47,0	3413,8	22,61
	4	46,5	3456,1	23,42
	5	46,8	3429,1	23,07

Table F1 Ultrasonic Dynamic Elastic Modulus for Pastes/continued

RATIO	SPECIMEN NUMBER	ULTRASONIC TRAVEL TIME T μ s	ULTRASONIC VELOCITY V ms^{-1}	ULTRASONIC DYNAMIC MODULUS GPa
2,4	1	45,5	3522,0	24,69
	2	46,1	3478,3	23,95
	3	45,6	3524,3	24,74
	4	45,8	3498,9	24,38
	5	46,7	3436,2	23,24

Table F2(a) Ultrasonic Dynamic Elastic Moduli for Granite Mortars

RATIO	SPECIMEN NUMBER	ULTRASONIC TRAVEL TIME μ s	ULTRASONIC VELOCITY V ms^{-1}	ULTRASONIC DYNAMIC MODULUS GPa
1,5	1	37,9	4069,3	43,33
	2	38,9	3993,6	35,61
	3	37,8	4071,6	37,09
	4	37,7	4072,9	36,66
1,8	1	36,1	4205,6	40,14
	2	35,0	4327,1	43,11
	3	36,8	4211,2	39,72
	4	36,4	4255,7	40,68
2,4	1	33,6	4461,8	46,24
	2	34,5	4438,6	45,76
	3	34,3	4455,3	45,85
	4	35,1	4297,7	43,25

Table F2(b) Ultrasonic Dynamic Elastic Moduli for Andesite Mortars

RATIO	SPECIMEN NUMBER	ULTRASONIC TRAVEL TIME T μ s	ULTRASONIC VELOCITY V ms ⁻¹	ULTRASONIC DYNAMIC MODULUS GPa
1,5	1	36,0	4252,3	42,83
	2	36,3	4167,8	41,11
	3	36,9	4159,2	40,83
	4	36,8	4114,1	39,90
1,8	1	35,8	4320,7	44,66
	2	34,3	4460,5	47,85
	3	35,5	4369,0	45,39
	4	34,6	4400,5	46,15
2,4	1	34,7	4420,7	46,36
	2	34,3	4460,5	47,28
	3	33,9	4526,8	49,75
	4	34,5	4447,0	47,13

Table F3(a) Ultrasonic Dynamic Elastic Moduli for Granite Concrete

STONE CONTENT kg/m ³	W/W RATIO	SPECIMEN NUMBER	ULTRASONIC TRAVEL TIME T μs	ULTRASONIC VELOCITY V ms ⁻¹	ULTRASONIC DYNAMIC MODULUS GPa
700	1,5	1	109,9	4485,9	47,05
		2	109,4	4469,8	46,72
	1,8	1	107,1	4593,8	49,28
		2	107,9	4587,6	49,86
	2,4	1		4700,3	52,37
		2		4703,1	52,42
1000	1,5	1	107,9	4569,0	49,36
		2	106,5	4633,8	50,73
	1,8	1	102,8	4795,7	54,69
		2	103,7	4761,3	53,65
	2,4	1	101,8	4835,5	56,27
		2	101,7	4818,1	56,00
1300	1,5	1	104,8	4723,3	53,88
		2	103,9	4732,9	54,06
	1,8	1	102,3	4826,5	55,90
		2	101,2	4896,2	58,05
	2,4	1	99,4	5000,0	60,75
		2	100,2	4930,1	59,33

Table F3(b) Ultrasonic Dynamic Elastic Moduli for Andesite Concrete

STONE CONTENT kg/m ³	c/w RATIO	SPECIM ⁿ NUMBER	ULTRASONIC TRAVEL TIME μs	ULTRASONIC VELOCITY V ms ⁻¹	ULTRASONIC DYNAMIC MODULUS GPa
700	1,5	1	103,1	4723,6	55,75
		2	105,3	4710,4	55,90
	1,8	1	101,9	4820,9	57,97
		2	101,1	4871,4	59,03
	2,4	1	99,6	4934,7	60,90
		2	97,5	5039,3	64,33
1000	1,5	1	101,3	4935,8	61,68
		2	98,1	4984,7	63,71
	1,8	1	97,1	5108,1	66,61
		2	98,5	5009,1	64,84
	2,4	1	94,7	5198,0	69,37
		2	96,1	5150,9	68,12
1300	1,5	1	97,0	5103,1	67,29
		2	96,4	5150,4	67,69
	1,8	1	94,2	5284,0	72,14
		2	94,0	5215,4	69,96
	2,4	1	90,4	5311,2	74,54
		2	92,2	5349,8	74,69

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Author Grills Frank

Name of thesis Static And Dynamic Elastic Modulus Testing Of Concrete And Its Constituents And Comparison Of Results With Theoretical Models. 1986

PUBLISHER:

University of the Witwatersrand, Johannesburg

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