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Compaction Properties of Roller Compacted Concrete

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Abstract

The compaction characteristics of extremely dry concrete are evaluated using a new method based on a variable vibration table. This method allows the study of the effect of vibration frequency, vibration time and acceleration on the properties of concrete. In this paper, a fundamental relationship linking energy of compaction to 'filled volume ratio' is used to assess the efficiency of compaction and to evaluate the optimum mix composition. Copyright © 1996 Elsevier Science Ltd.

INTRODUCTION

Roller compacted concrete (RCC) is an extremely dry concrete which is very difficult to compact by the normal methods used for workable concrete. RCC is used for the construction of dams and pavements. Similar consistency concrete is used for units like pipes cast in factories using special high energy compaction equipment. Compaction in the field is carried out using heavy vibratory rollers which can reduce the porosity of RCC to relatively low values.[1–3] Low porosity concrete leads to high strength and long term durability and thus it is important to optimise compaction procedures so that the compacted material is adequately packed. It has been found that an increment of 1% on the porosity of concrete will reduce the compressive strength by 3–5 MPa.[4] To ensure that RCC is resistant to freeze–thaw, a durability factor of 60% has been proposed by Kuzu *et al.*[5] They have indicated that the porosity of RCC should not be more than 3%.

To ensure appropriate engineering and performance properties, RCC mix proportions should be such that they are not difficult to compact and therefore have adequate compaction properties for roller operation. The major variables which influence compactibility are mix composition, mineral aggregate size distribution, shape of sand and coarse aggregate particles and free water content.

Kokubu[6] has proposed a new test method for measuring compactibility of RCC by quantifying the compactive effort required to achieve maximum 'filled volume ratio'. This laboratory method is also used to study the importance of mix composition variables and thus to optimise mix composition for maximum compaction. There are few reports in the relevant literature which have provided data on the compaction variables which affect the properties of RCC. For example, Kolek[7] reported compaction curves of stiff concretes, Murata[8] produced data of very stiff concrete compaction in relation to the product of kinetic energy multiplied by vibrating time and Cabrera[9] has produced data on the effect of w/c ratio on the compaction of high-volume fly ash dry concretes. However, data on the energy of compaction requirements is very scanty.

This paper presents data on the effect of vibration parameters on the compaction of dry concrete. It gives data on the effect of mix composition by assessing the compactibility of various RCC mixes where sand content, water content and w/c ratio effects on compaction are

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quantified by the relationship between 'filled volume ratio' (γ) and compactive effort' (E).

MATERIALS

Cement

The cement used for the laboratory experiments was an ordinary Portland cement (opc) conforming to JIS R 5210 (Japanese standards).[10]

Aggregates

The coarse aggregate used was a 20 mm maximum size crushed aggregate conforming to the Japanese standard JIS A 5005.[11] Two types of sand of a maximum size of 4·75 mm, were used, pit sand for the experiments of series I and a blended sand for the experiments of series II. The sands conformed to the Japanese standard requirements of JIS A 5308.[12] Relevant properties of the aggregates are given in Table 1.

MIX PROPORTIONING

The mix proportioning was based on the method proposed by Nakahara *et al.*,[13] which consists basically of controlling the mortar to inter-aggregate voids ratio (k_m) and the cement paste to inter-sand voids ratio (k_p). The sand/aggregate ratio (s/a) is obtained from the values of k_m and k_p.

The equations used for mix proportioning are:

$$k_m = \frac{m}{G.e_g} \tag{1}$$

$$k_p = \frac{p}{S.e_s} \tag{2}$$

$$s/a = \frac{k_m.e_g.r_g}{(k_m.e_g.r_g + k_p.e_s.r_s + 1)} \tag{3}$$

$$e_g = \frac{1}{T_g} - \frac{1}{r_g} \tag{4}$$

$$e_s = \frac{1}{T_s} - \frac{1}{r_s} \tag{5}$$

Where:

k_m = mortar to inter-aggregate voids ratio
m = volume of mortar per unit volume of concrete
G = aggregate content per unit volume (kg/m^3)
k_p = paste to inter-sand voids ratio
p = volume of cement paste per unit volume of concrete
S = content of sand per unit volume of concrete (kg/m^3)
s/a = sand/aggregate ratio expressed as percentage
r_g = saturated surface dried (SSD) relative density of coarse aggregate
r_s = saturated surface dried (SSD) relative density of sand
T_g = (SSD) density of coarse aggregate (kg/m^3)
T_s = (SSD) density of sand (kg/m^3)
W = free water (above saturated surface dry conditions)

The mix proportions of the concretes used in the study are shown in Table 2.

Table 1. Physical properties of the aggregates used

Series	*Material*	*Relative density SSD*	*Relative density Oven dry*	*Bulk density ton/m^3*	*Solid volume ratio (%)*	*FM*	*Absorption (%)*
I	Pit sand	2·62	2·59	1·79	69·1	2·90	1·07
	Crushed stone	2·64	2·61	1·57	59·9	6·67	0·92
II	Blended sand	2·57	2·61	1·76	68·5	2·75	1·41
	Crushed stone	2·60	2·62	1·55	58·8	6·65	1·55

SSD — Saturated Surface Dry.
FM — Fineness Modulus.

Table 2. Mix proportion of concrete

Series	k_m	k_p	*W/C*	*s/a*	*W*	*C*	*S*	*G*
I — Variable W	1·60	1·30	0·35	0·404	100	286	857	1274
	1·60	1·11	0·35	0·418	90	257	907	1274
II — Variable s/a	1·40	1·79	0·35	0·340	115	329	694	1350
	1·50	1·69	0·35	0·362	115	329	739	1305
	1·60	1·59	0·35	0·383	115	329	781	1262
	1·70	1·52	0·35	0·402	115	329	820	1223
	1·80	1·45	0·35	0·421	115	329	858	1185
II — Variable W	1·50	1·33	0·35	0·385	100	286	814	1304
	1·54	1·41	0·35	0·385	105	300	804	1289
	1·57	1·50	0·35	0·385	110	314	794	1274
	1·68	1·59	0·35	0·385	115	329	784	1258
	1·76	1·68	0·35	0·385	120	343	775	1243
II — Variable w/c	1·64	1·65	0·30	0·385	110	367	778	1247
	1·57	1·50	0·35	0·385	110	314	794	1274
	1·52	1·39	0·40	0·385	110	275	807	1294

TESTING PROCEDURES

Compactibility test

Kokubu *et al.*[6] developed an apparatus consisting of an electromagnetic table vibrator capable of applying a centrifugal force of 4kN and frequencies ranging from 5 to 3500 Hz.

The 'filled volume ratio' (γ) defined by eqn (6) is calculated during vibration by measuring the settlement of the concrete sample which is contained in a cyclinder of 100 mm in diameter and 200 mm in height and which is subjected to a surcharge of 20 kg.

$$\gamma = \frac{V_s}{V_t} \times 100 \tag{6}$$

Where:

γ = filled volume ratio(%)
V_s = volume of solids+water
V_t = total volume of sample

The vibrating conditions for the experiments reported in this paper where:

acceleration of 2, 5 and 8 times the acceleration of gravity.
frequencies of 75, 100 and 150 Hz.

The settlement of the concrete in the cyclinder is automatically measured every 0·3 s using a laser displacement apparatus and the reading is converted to a value of γ. The compaction effort is calculated from the vibrating parameters, vibrating time and the bulk density of the concrete specimen. This is explained in detail in the section of results.

The relation of γ and compaction effort (E_v) can be approximated by a statistical equation of the following form:

$$\gamma = \gamma_i + (\gamma_f - \gamma_i)(1 - \exp(-bE_v^d)) \tag{7}$$

Where:

γ_i = initial filled volume ratio
γ_f = final filled volume ratio
E_v = compaction effort (Joules/litre)
b, d = experimental constants

An example of the γ vs E_v relation is shown in Fig. 1. As can be seen, the value of γ_f is the potential filled volume ratio achieved at $E_v = \infty$. The compaction efficiency (C_e) is defined in this figure as the gradient of the relationship at a compactive effort of 1 J/l and it is used to quantify the efficiency of the compaction process. A compaction effort to achieve a value of γ equal to 98% is considered the maxi-

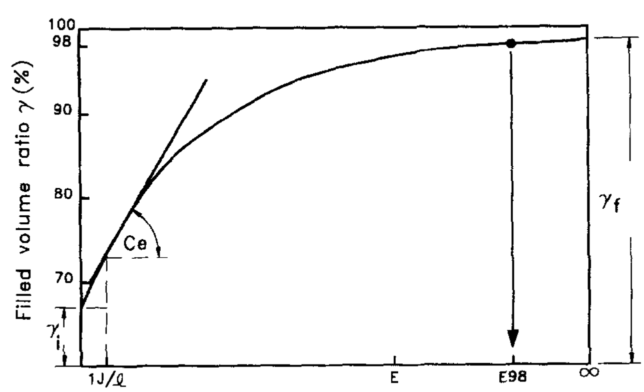

Fig. 1. Compaction curve.

mum effort (E_{98}) required to achieve practically maximum density.

Modified Vebe test

This test uses the Vebe apparatus. The vibrating conditions of this test are:

acceleration 5 g
frequency 50 Hz
amplitude 0·5 mm
surcharge mass 20 kg

The density of the specimen is calculated from the height of the sample measured by stopping the test at 3, 10 and 60 s.

Marshall Hammer test

This is a test used for compacting bituminous composites.[14] The compaction effort is applied via a hammer of 4·5 kg dropping from a height of 457 mm. The height of the sample is measured automatically after every drop of the hammer.

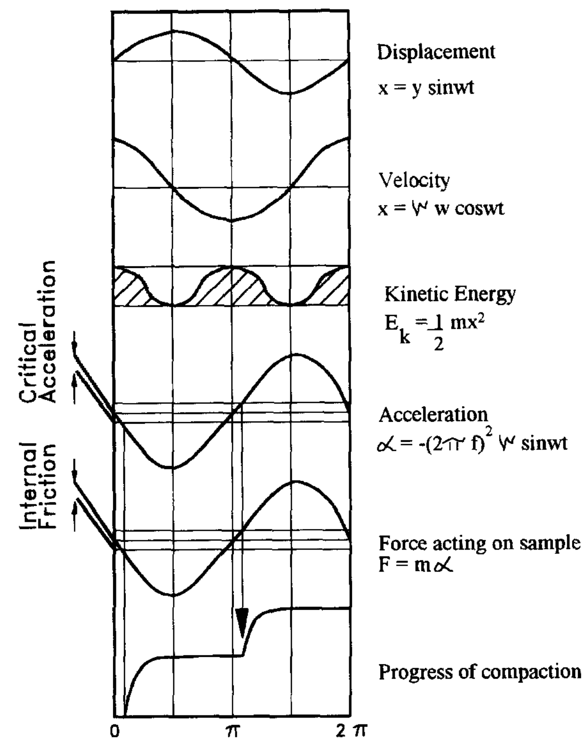

Fig. 2. Schematic representation of the process of compaction using the vibrating table apparatus.

RESULTS AND DISCUSSION

Calculation of compaction effort

Compactibility test

Figure 2 is a simplified representation of the vibrating compactibility test. The compaction effort (E_v) is expressed as kinetic energy (E_k):

$$E_k = \frac{1}{2}.m\left[\frac{\alpha_{max}}{2\pi f}\right]^2 \qquad (8)$$

Under sinusoidal acceleration the vibrating energy input is two times per cycle, therefore the vibrating energy of compaction on a unit mass of concrete during vibrating time (t) is expressed by the following equation:

$$E_v = \frac{m.\alpha_{max}^2 t}{4\pi^2 f} \qquad (9)$$

Where:

E_v = compaction effort (J/l)
t = vibration time (s)
m = unit mass of concrete (kg/l)
α_{max} = maximum acceleration (m/s^2)
f = frequency (Hz)

Figure 3(a) shows the relation between (γ) and (t) for frequencies of 75, 100 and 150 Hz and for accelerations of 2 g, 5 g and 8 g. The trends shown in this figure seem to indicate that better compaction is achieved by increasing acceleration (α) and decreasing the frequency (f), however, when the value of (γ) is plotted against compaction effort (E_v) (Fig. 3(b)) it becomes apparent that the frequency of vibration has practically no effect on the maximum value of compaction achieved but very importantly there appears to be an optimum value of (α) above which there is practically no increase in compaction, i.e. the value of γ becomes a constant.

Tests were carried out using mixes with different amounts of water (90 and 100 kg/m^3) to investigate if the effect of acceleration was different, however as shown in Fig. 4 beyond an acceleration value of 2·5 g the final filled volume ratio γ_f becomes constant.

Modified Vebe test

Figure 5 shows the acceleration measured on the vibrating Vebe table including the surcharge plate of the apparatus. The acceleration measured on the table is 6 g, different from the nominal value of 5 g expected for this appara-

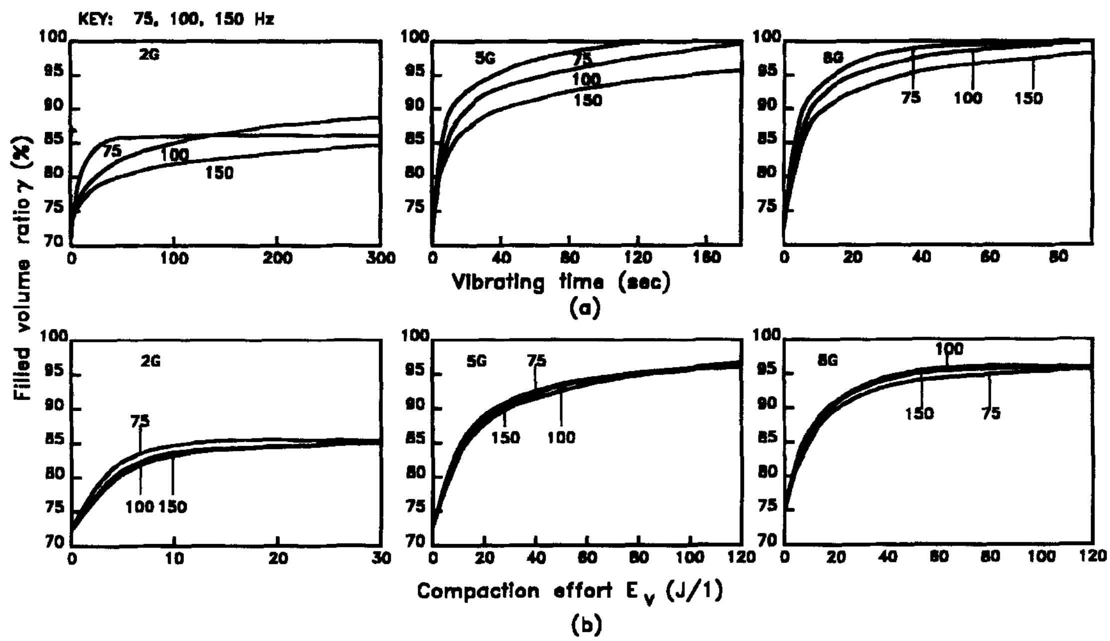

Fig. 3. Effect of frequency and acceleration on compaction of concrete.

tus. The acceleration of the surcharge plate is 1·5 g upwards and 1g downwards. As shown in Fig. 5 the acceleration of the Vebe table is not in phase with the acceleration of the surcharge plate, this is due to the visco-elastic nature of fresh concrete. Because the plate has the effect of tamping the surface of concrete, this virtually must increase the energy of compaction.

The mass of the surcharge plate specified in different standards is different, for example the Japanese standard specifies 20 kg, the ASTM C 1170 standard 22·7 kg, the American Corps of Engineers Standard 12·5 kg. It has been reported that the heavier the surcharge, the smaller the Vebe time of vibration required.[15] This finding appears to confirm the contribution of the plate effect on the increase of the energy of compaction.

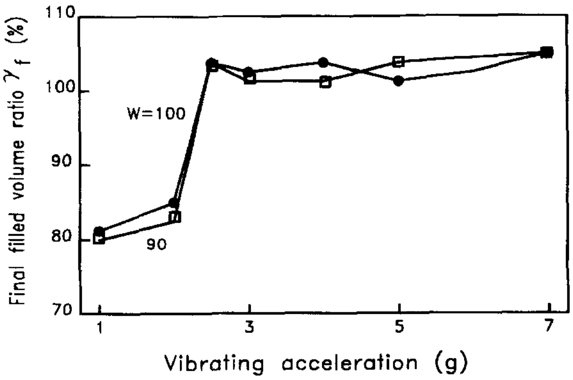

Fig. 4. Effect of acceleration on ultimate filled volume ratio.

Marshall Hammer test

In this test the energy of compaction is obtained by assuming that the potential energy can be expressed as compactive effort. The numerical relation to calculate this compactive energy is:

$$E_m = n\text{Mgh/v} \qquad (10)$$

Where:
E_m = Marshall compaction effort (J/l)
n = number of blows of the Marshall Hammer
m = mass of the hammer (kg)
g = acceleration due to gravity (m/s^2)
h = height of hammer drop (m)
v = volume of concrete (l)

RELATIONSHIP BETWEEN COMPACTIVE EFFORT AND FILLED VOLUME RATIOR

The relationships between compaction effort and filled volume ratio obtained from the compactability test, the Vebe test and the Marshall Hammer test are shown in Fig. 6.

The compaction curves of the compactibility test and the Vebe test are shown to be similar, but the relations from the hammer test are different. The filled volume ratio of the hammer test at any energy is lower than that of the vibrating methods. The reason seems to be that portion of the compactive energy in the ham-

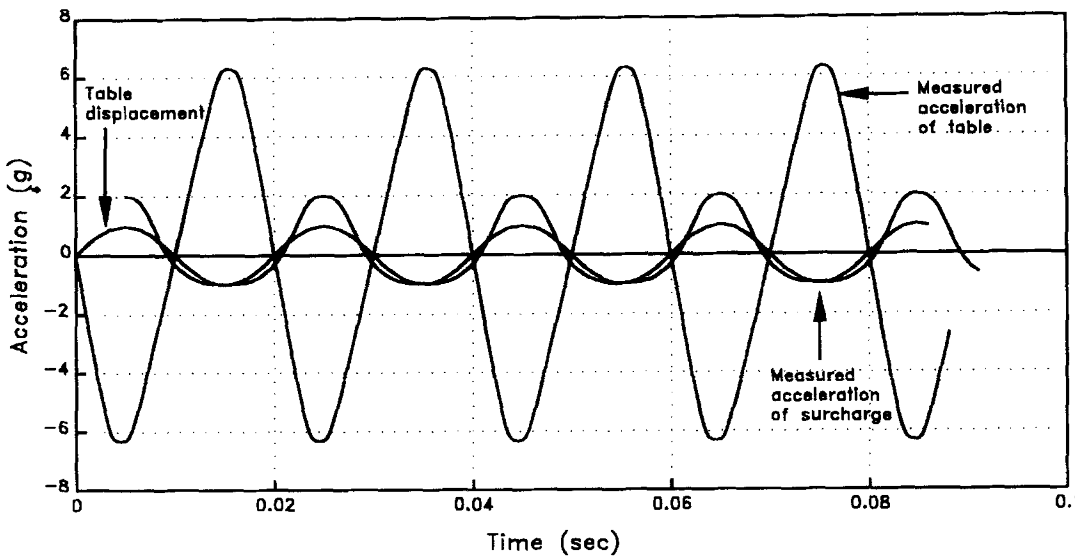

Fig. 5. Acceleration measured on the Vebe vibrating compaction test apparatus.

mer test is consumed in breaking particles[15] or internal friction between aggregates.

To detect the possibility of compactive energy loss in the hammer test, the particle size distribution (PSD) of the aggregates in the concrete was analysed before and after testing. The concrete was washed through a set of standard sieves. The PSD of the natural aggregates (sand and gravel) after mixing was almost the same as that of the distribution resulting from the specified mix proportions and gradings of the fine and coarse aggregates. The differences between the calculated distribution and the measured one were within 0·05 of the fineness modulus of whole aggregate.

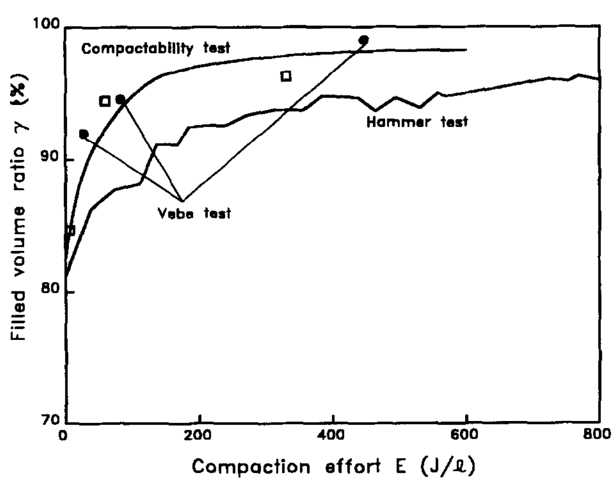

Fig. 6. Relationship between compactive effort and filled volume ratio for different compaction methods.

Tests carried out before and after compacting concrete specimens with the compactibility apparatus and the Vebe table confirmed that there is no degradation of aggregates whether they are natural or crushed. However, tests with the Marshall hammer showed that crushed aggregates and sands degraded slightly during the compaction process. Figure 7 shows the extent of the degradation of the aggregates, this

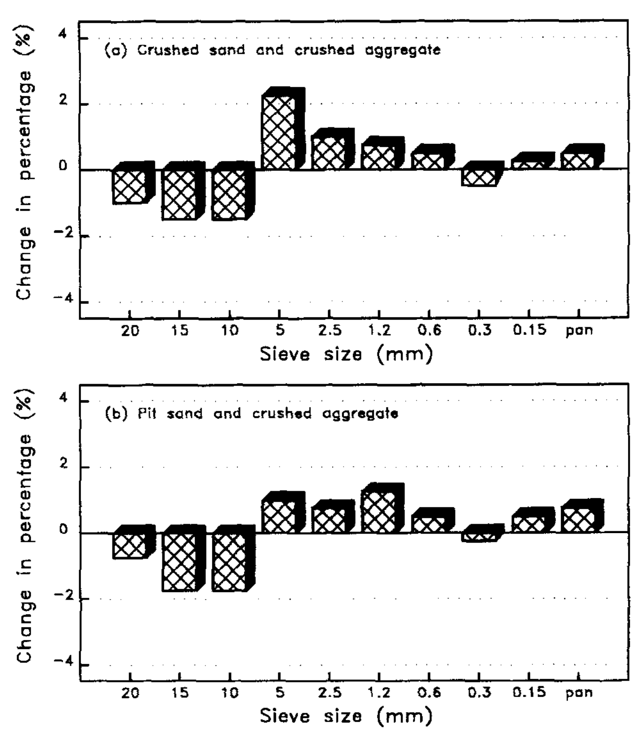

Fig. 7. Change of particle size distribution after compaction with the Marshall hammer.

may affect the compaction characteristics of concrete during the Marshall hammer test and therefore the results might not be representative of the original mix.

EFFECT OF MIX PROPORTIONING ON COMPACTION CHARACTERISTICS

Sand/aggregate ratio

In a concrete mix of w/c = 0·35 with water content equal to 115 kg/m^3, changes in the sand content result on increased values of γ_i but reduced values of compaction efficiency C_e — this is clearly shown in Figs 8(a) and (b). Large amounts of sand reduce the volume of inter-coarse aggregate voids, but increases the inter-sand voids.

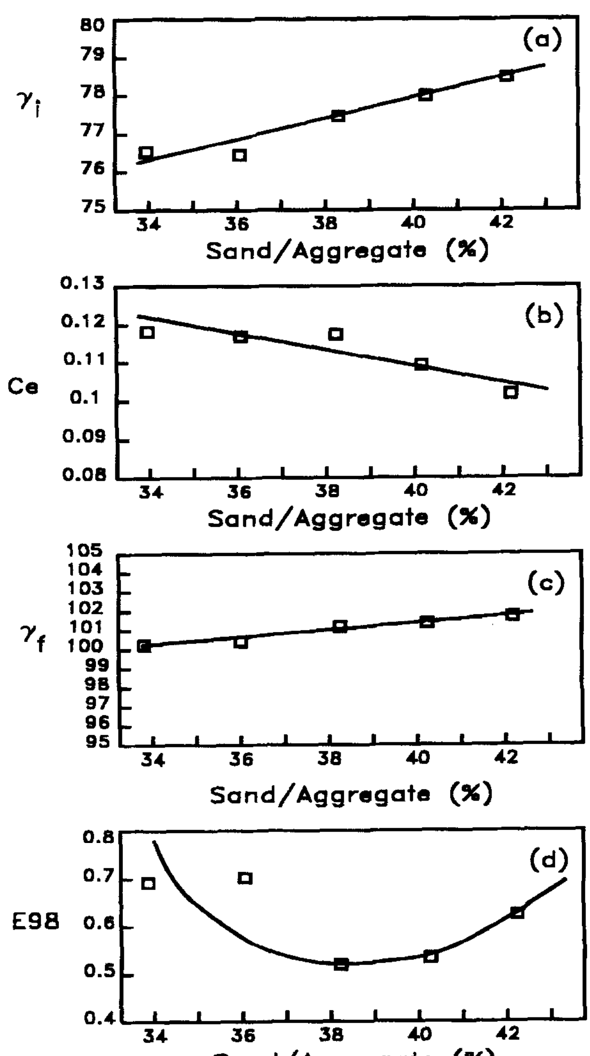

Fig. 8. Effects of sand percentage on compactibility.

The reduced value of C_e is a clear indication that the reduction of the small inter-sand voids are hardly reduced during vibration. The value of γ_f increases slightly with increasing sand/aggregate ratio as shown in Fig. 8(c). The overall effect of the observed trends occurring with changes in the sand content is that there is an optimum percentage of sand for minimum application of energy to achieve maximum compaction. This is shown in Fig. 8(d). Figure 9 shows that the effect of sand/aggregate ratio is also demonstrated when compacting concrete with the Vebe table and the Marshall hammer.

Water content

For the mixes tested, changing the amount of water from 100 to 120 kg/m^3 in a mix with optimum s/a percentage (series II in Table 2) of 38·5 and w/c = 0·35, the effect is negligible with relation to γ_i, large increase on the value of C_e, an increase of the γ_f value up to 102% with 105 kg/m^3 of water. This increase to 102% is due to the loss of part of the mortar into the opening between the top plate and the wall of the container and therefore should be taken as 100% if corrections are made.

The overall effect of increasing the amount of water in a concrete mix is to reduce the energy required to attain maximum compaction. These trends are shown in Figs 10(a), (b), (c) and (d).

Water cement ratio

The tests to assess the effect of w/c ratio on compaction of dry concretes were carried out using, mixes with optimum sand/aggregate ratio and a total water content of 110 kg/m^3. The results confirmed the fact that as w/c ratio increases the E_{98} value decreases, but this decrease is negligible when compared to the reductions of energy required for full compaction obtained by changing the total water content (Table 3).

OPTIMAL MIX PROPORTIONING

The results discussed indicate that the optimal mix should be obtained by optimising the s/a ratio since there is an optimum maximum sand/aggregate ratio for minimum energy applied for full compaction and that the appropriate

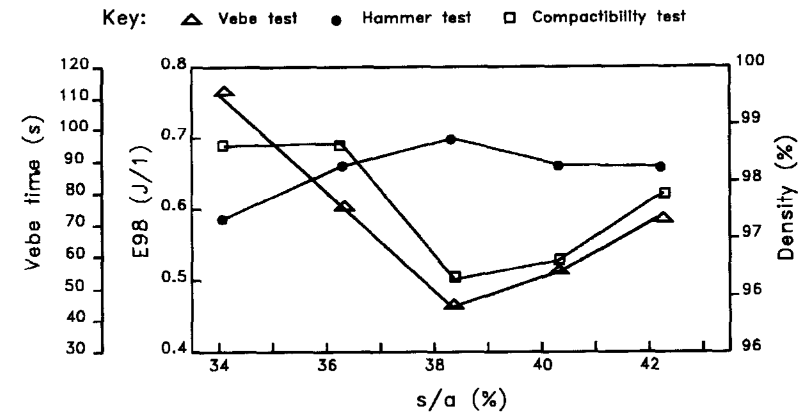

Fig. 9. Optimum sand percentage resulting from different test methods.

amount of water should be that which corresponds to the large change of slope of the relation between E_{98} and water content. As shown in Fig. 10(d) the relation approximates an exponential decay function and therefore there is an 'optimum' amount of water beyond which changes in the E_{98} value are negligible.

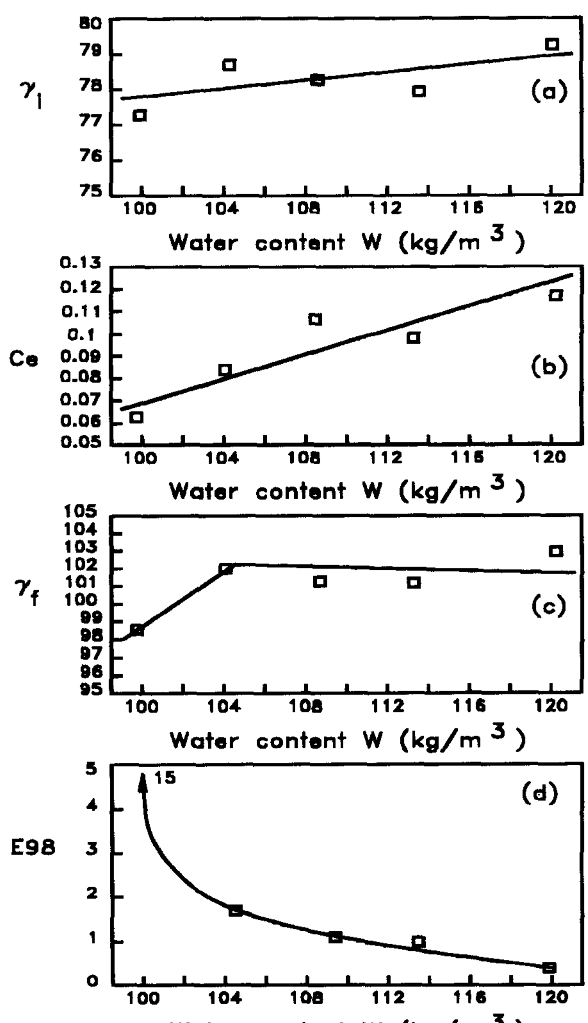

Fig. 10. Effects of water content on compactibility.

CONCLUSIONS

From the experimental work presented in this study, the following conclusions are offered.

(1) The evaluation of the compaction characteristics of Roller Compacted Concrete show that maximum compaction (γ_f) is achieved by vibrating the concrete at low acceleration. Beyond 2·5g the maximum compaction does not change.
(2) When evaluating concrete by the compaction energy calculated from the parameters used in the vibrating table apparatus it is shown that frequency of vibration does not influence the maximum value of 'final filled volume'.
(3) The Marshall Hammer method produces measurable degradation of the aggregates during cmpaction and therefore further studies are required to assess the suitability of this test.
(4) The study shows that the sand content of concrete expressed as the sand/aggregate ratio as well as the water content are the most important mix proportioning parameter for the optimal mix proportioning of roller compacted concrete.
(5) The reduction of energy vs the total water content of a concrete mix can be expressed as a decay function. The optimum amount of total water for compaction of a roller compacted mix

Table 3. Effect of w/c ratio on the compactibility of concrete with s/a = 38·5% and total water content of 110 kg/m^3

Parameter		*w/c*	
	0·30	*0·35*	*0·40*
Initial filled volume γ_i	77·20	77·30	78·80
Compaction efficiency C_e	0·10	0·10	0·09
Final filled volume γ_f (%)	100·50	101·00	102·30
Compactive effort E_{98}(J/l)	1·13	0·81	0·80

may be obtained by selecting the amount of water beyond which the energy reduction is minimal.

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