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THE CORRELATION OF NON-DESTRUCTIVE TEST RESULTS WITH CONCRETE STRENGTH

by

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Synopsis

Rebound hammer and ultrasonic pulse velocity tests were performed on 6" x 6" x 6" cubes cast and stored under a variety of conditions that could be expected for concrete in Sri Lankan building works, before their cube strengths were determined. It was therefore possible to find correlation between these non-destructive test results and cube strength. Although a distinction was found between the behaviour of air cured dry cubes and water cured wet cubes, within these categories a single correlation was sufficient to account for the variations in strength caused by variations in other parameters, for the ranges investigated. When only pulse velocity measurements are available for the assessment of the strength of concrete in a structure, it is argued that the use of the dry cube correlation will give a reasonable and conservative lower bound estimate for equivalent cube strength.

1.0 Introduction

The concrete cube (or cylinder) test has become the most universally accepted measure of concrete strength. However, although it may provide a good indication of the potential strength of a given mix, it is not a good index of the quality of the concrete in the structure itself, which depends also on the workmanship factors of curing and compaction.

Many in-situ tests to assess the quality of concrete in structures have been developed (1). While some of these are designed to be used as pre-planned tests (eg. the pull-out test), most of them are generally used in unforeseen circumstances - for example, when the cube test results for a particular batch of concrete has failed and it is desired to avoid demolition by proving the adequacy of the as-cast concrete; or when the residual strength of a deteriorated structure has to be assessed. In such situations, it is highly desirable for the in-situ tests to be as "non-destructive" as possible.

While obtaining core samples and testing them for strength is perhaps the most reliable in-situ test (2), these tests are relatively expensive to perform and may have to be carried out in conjunction with a greater number of other in-situ tests. Furthermore, core testing can be considered as being "partially destructive". Other in-situ tests, such as Rebound Hammer and Ultrasonic Pulse Velocity tests, are genuinely non-destructive in nature and easier to perform. However their reliability is lower.

One of the ways to gain greater confidence in such non-destructive tests is to calibrate them extensively with respect to strength. Since such calibrations are sensitive to concrete constituents and conditions, the proper use of these tests in Sri Lanka will require calibrations performed on concrete made with local raw materials. This paper reports some laboratory based calibrations for Rebound Hammer and Ultrasonic Pulse Velocity tests.

2.0 Experimental Details

2.1 Test Programme

The objective of the investigation was to perform both the non-destructive tests and crushing tests on 6" x 6" x 6" cubes cast and stored under a variety of conditions. Three series of tests were performed and the variables involved are depicted in Table 1. The cement used was Ordinary Portland Cement, while the coarse aggregate was granitic and the fine aggregate quartzite river sand.

The parameters investigated were Concrete Mix Proportions, Compaction, Curing and Age of Testing. The parameter ranges were chosen so as to encompass values that could be found in reinforced concrete buildings in Sri Lanka, assuming that the workmanship factors would result in concrete qualities from "normal" to "defective"

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For example, although 1:2:4 (v/v) concrete is generally specified for reinforced concrete buildings, it was assumed that the mix may become as lean as 1:3:6 (v/v). It should be noted that batching of dry ingredients for (v/v) mixes was done as per ICTAD Specifications (3).

Although an attempt was made in series B to increase slump by increasing the w/c ratio in mixes 4-6, the resulting slumps were not very high; this could be considered a slight shortcoming in the experimental programme. It was remedied in Series C, where a slump of 135 mm was obtained.

The degree of compaction was also varied from full compaction (where the cubes were vibrated in 3 layers on a vibrating table until air bubbles were eliminated) to zero compaction (where the cube moulds were merely filled with concrete and levelled off, using minimum effort).

The water cured cubes provided a "standard" measure, while the air cured cubes (stored in the laboratory environment) were expected to reflect in-situ concrete more accurately.

The duration of testing, ranging from 1 to 43 days, would just about cover situations where a concrete structure required an in-situ test after the failure of 7 or 28 day cube test results.

Two specimens per condition were tested in Series A while three per condition were tested in Series C. Series B was in fact a full factorial experimental design (more details of which will be reported subsequently) to test the effects of Concrete Mix, Slump, Compaction and Curing on various cube properties and hence only 1 cube per condition was tested.

2.2 Test methods

At the appropriate age of testing, a cube was first tested for ultrasonic pulse velocity, using the PUNDIT test equipment. Readings were taken at the centre of the two available pairs of opposite cast faces, using the direct method of testing (1); the average of these results was taken for subsequent analysis. Great care was taken to ensure that there was good contact between the transducers and the cube faces by using a grease couplant.

After this, excess grease was wiped off from the surfaces of the cube, which was then placed between the platens of a compression testing machine. The load was increased gradually until it corresponded to a stress of 7 N/mm^2 on the cube. at this point, 9 readings were taken on each of the available pair of opposite cast faces with a rebound hammer of impact energy around 2.2 Nm. The average of these readings was taken for subsequent analysis. The rebound hammer test was performed in accordance with the specifications in the relevant British Standard (4).

Finally, the cube was loaded to failure in the same compression testing machine, the load being increased from 7 N/mm^2/min (5) to the failure stress at a rate of 15 N/mm^2/min.

3.0 Rebound Hammer Correlations

The results of concrete cube strength versus rebound number are shown in Figure 1. It should be noted that only compacted cubes have been used, as the uncompacted cubes had an open texture with aggregate particles exposed; Furthermore, the correlation has been plotted only for the air cured cubes which were dry, since the wet surfaces of the water cured cubes would have caused discrepancies (6)

In this example, all the wet cured cubes gave low average rebound numbers of between 14.8 and 17.6 for a strength range of 11.6 to 28.1 N/mm^2. It seems therefore that the Rebound Numbers of wet specimens are more characteristic of their seemingly similar soft surfaces than their varying compressive strengths.

Where the air cured dry cubes are concerned, the correlation between cube strength and rebound number is linear, with an r^2 value of 0.79. Such linear correlations have been obtained by many other investigators (1,7,8). Figure 1 seems to indicate that the correlation is independent of mix proportions and testing age within the ranges of these parameters indicated in Table 1.

However, the effect of age beyond 3 months is reported to affect the correlation, due to surface carbonation and other factors (6). Hence, the rebound hammer test is not very reliable for assessing absolute values of in-situ concrete strength; it can, however, be used profitably to make comparative measures of strength within a given structure.

4.0 Ultrasonic Pulse Velocity Correlations

4.1 Factors affecting the correlations

Figure 2 indicates the relationship between the cube strength and pulse velocity for dry air cured cubes of different types. The figure indicates that they all fall on the same curve, with a reasonable degree of scatter. In fact, even the uncompacted cubes (shown in dark circles, as opposed to open symbols) form part of the same curve. This has very significant implications for the testing of concrete in structures; it means that a single correlation between cube strength and pulse velocity can pick up differences in strength due to a variety of causes, such as changes in mix proportions including water/cement ratio), degree of compaction and age of testing. Furthermore, the ranges of the above variables investigated (see Table 1) are expected to cover the situations arising in most building works in Sri Lanka, as argued in Section 2.1

It should be noted that Facaoaru (9) and Elvery & Ibrahim (10) report that the strength-velocity correlation is dependent on cement content and aggregate/cement ratio respectively. However, this dependence diminishes as the mixes become leaner, with Elvery & Ibrahim stating that the influence of an aggregate/cement ratio change from 3.5 to 5 is negligible (10). Since the mixes in the present investigation are in fact leaner than this range, it would be reasonable and also consistent with the above investigators' findings to state that mix proportions leaner than 1:2:4 do not influence the correlation curve. Furthermore, both Facaoru (9) and Elvery & Ibrahim (10) also report that the correlation is insensitive to water/cement ratio and degree of compaction, as discovered in the present investigation too.

The age of testing is also cited by Facaoaru (9) as affecting the strength-velocity correlation. It must be admitted that the test programme described in Section 2.1 is not particularly well suited to isolate this effect of the testing age. Hence, the lumping of data points corresponding to ages of 1 to 43 days may be introducing a certain degree of approximation to the correlation curve.

While Figure 2 depicted only dry cubes (of which there were a greater variety), Figure 3 shows both dry cubes (which were air cured) as well as wet cubes (which were water cured). The shading of the cube points, in contrast to the open symbols used for the dry cube points, brings out the difference between the two types of cubes; all the shaded points, with a few exceptions, lie below the open symbols, indicating that different correlations be made for dry and wet cubes respectively.

The need for the above distinction has been highlighted by Tomsett (11) as well. In fact, for two cubes of equal strength, the wet cube will yield a higher pulse velocity than the dry cube. This may be due to the higher velocity of the ultrasonic pulse in a more saturated medium (11), as well as the lower velocity of the pulse in concrete which contains greater microcracks due to drying (9).

Hence, when arriving at mathematical expressions for the cube strength vs. pulse velocity correlation, they were fitted separately for the dry and wet cubes.

4.2 Mathematical Expressions

The wave velocity of the ultrasonic pulse, V, is given by (1),

$$V^2 = (1-\mu).E_d/(1+\mu).(1-2\mu).\rho \quad .... (1)$$

which can be rearranged as

$$E_d = \rho V^2.(1+\rho).(1-2\rho)/(1-\mu) \quad .... (2)$$

where E_d is the dynamic modulus of elasticity, ρ is the density and μ is Poisson's ratio.

Furthermore, Ed is considered as being linearly correlated with E_c, the static modulus of elasticity (12), which in turn is considered to be proportional to either the square root (13) or cube root (12) of strength, f, i.e.

$$E_c \propto f^n \quad .... (3)$$

where n = 1/3 in the British code (12)
and n = 1/2 in the American code (13).

From the form of expressions (2) and (3), it may be concluded that strength should be proportional to a power of pulse velocity, i.e.

$$f \propto V^m \quad .... (4)$$

where m may be in the range 4 to 6.
As such, data was fitted with an expression of the form,

$$f = k1.V^{m1} \quad .... (5)$$

where k_1 and m_1 are constants.

However, the literature (1,9,11) indicates that data is also fitted well by an empirical expression of the form

$$f = k_2.\exp(m_2V) \quad .... (6)$$

where k_2 and m_2 are constants. Hence, this expression was also used to fit the current data.

Furthermore, there have been claims that a combined correlation, using both pulse velocity and rebound hammer results will be better (7). Hence, where the dry cubes were concerned (for which there were rebound hammer results as well), the data was refitted, using expressions of the form

$$f = k_3 + k_4.N + k_5.V^{m1} \quad ....(7)$$

and

$$f = k_6 + k_7.N + k_8.\exp(m_2V) \quad ....(8)$$

where m_1 and m_2 were set at the values obtained from the previous curve fitting using pulse velocity data alone, while k_3 to k_8 are constants arrived at by regression analysis; N is the rebound number.

The goodness of fit from these different approaches can be assessed by comparing the r^2 value, adjusted for the degrees of freedom (Table 2).

All the r^2 values in Table 2 are quite high. However, the inclusion of the extra variable of rebound number seems to decrease r^2 marginally; hence, for this reason and also on the basis of the principle of parsimony, a two parameter model is preferred to a three parameter one.

When comparing models (A) and (B) in Table 2, model (B) gives slightly better r^2 values for both dry and wet cube correlations. Hence, model (B) was chosen as the most appropriate mathematical expression for the cube strength vs. pulse velocity correlation.

The two different expressions for dry and wet cubes are shown plotted as straight lines in a semi-log plot in Figure 4. The gradients of these lines are 1.24 and 1.19 respectively and the lines are virtually parallel in semi-log space, the dry cube line representing a percentage increase in strength of around 7% over the wet cube line. These values can be compared with that of 1.1 obtained by Facaoaru (9) on the one hand and values of 1.69 and 1.54 obtained by Tomsett (11) on the other.

The exponents of V in Model (A) are 4.82 and 4.75 for the dry and wet cube correlations respectively (See Table 2). As expected, they fall between 4 and 6 and can be compared with the value of 5.01 obtained by Nasser and Al-Manaseer (8).

5.0 Estimating In-situ Concrete Strengths

The great difficulty in using these results for the estimation of concrete strengths in structures is the uncertainty regarding the moisture condition of the concrete in the structure. Figure 5 (after reference 11) illustrates the difference between a wet cube correlation and one for the concrete in a structure, where the difference in pulse velocity arises as a result of variations in strength as well as moisture content. It is therefore too conservative to use the wet cube correlation to estimate the strength of concrete in actual structures (11).

If a fair number of cores (around 10) are being tested along with pulse velocity readings, the best approach would be to calibrate the pulse velocity readings with the core strengths. If core testing is not carried out, one would have to use the correlations in Figure 4 in a judicious manner.

In situations where the parameters of the concrete in the structure can be expected to be within the ranges defined in Table 1 and where this concrete is being tested after the failure of test cube results i.e. where the testing would take place up to 6 weeks after placing, the dry cube correlation would be more appropriate, as the moisture condition in the structure would be more closely approximated by the dry cubes than by the wet ones.

Even if the structure is tested some time after 6 weeks, using the dry cube correlation in Figure 4 would give a conservative estimate. This is because concrete that has dried out more gives lower pulse velocity readings for higher strengths. A dry 1:2:4 cube from series A tested at 13 months yielded a pulse velocity of 4.66 km/s, which would be converted by the dry cube correlation to a cube strength of only 32.3 N/mm², whereas its actual strength was 41.1 N/mm². A similar phenomenon has also been observed for oven dried cubes (14).

If the structure to be tested looks very wet, perhaps after heavy rain, it is better to wait for some drying of the concrete to take place. In the most extreme case, if concrete that has a moisture level corresponding to the wet cubes is tested for pulse velocity and the dry cube correlation used to estimate the strength, it will be over-estimated by around 7%. However, the strength of wet concrete is generally increased by 10% when it is expected to be dry in subsequent service (1), which is the case in most building works. Hence the use of the dry cube correlation at all times, without any provision for strength increase due to drying, will give a reasonable and conservative lower bound for the strength of most concrete in Sri Lankan buildings.

It should be pointed out that Tomsett (11) advocates a slightly different approach to assessing the strength of concrete in structures. That approach however, requires correlations to be made between laboratory cubes and cores from concrete elements such as slabs; furthermore, it does not fully deal with the problem of variable moisture conditions in actual structures.

6.0 Conclusions

1. The rebound number of wet cubes appears to be more characteristic of their seemingly similar soft surfaces than their varying compressive strengths.
2. The correlation between cube strength, f (in N/mm²) and rebound number, N for the air cured dry cubes tested here was a linear one of the form $f = -12.88 + 1.39\,N$, for the range of parameters defined in Table 1.
3. It was found that a single correlation between cube strength and pulse velocity could pick up differences in strength due to a variety of causes such as changes in mix proportions (including water/cement ratio), degree of compaction and age of testing, within the limits defined in Table 1.
4. The best mathematical expression to define the correlation between cube strength, f (in N/mm²) and

pulse velocity, V (in km/s) was found to be of the form f = k.exp(mV), where k and m took the values of 0.100 and 1.24 for dry cubes and 0.094 and 1.19 for wet cubes respectively, the dry cube correlation representing a percentage increase in strength of around 7% over the wet cube one.

5. In situations where the pulse velocity technique alone is available for the assessment of the strength of concrete in structures, for most reinforced concrete building works in Sri Lanka, a reasonable and a conservative lower bound for the equivalent cube strength of the concrete in the structure can be obtained by using the dry cube correlation in Figure 4.

7.0 Acknowledgments

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8.0 References

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Table 1 - PARAMETER RANGES FOR THE EXPERIMENTAL PROGRAMME

	Concrete Mix	Compaction	Curing	Testing Age
Series A	1:2:4(v/v);w/c=0.50;slump=5mm 1:3:6(v/v);w/c=0.64;slump=0mm	Full compaction	Air cured	Various from 1 to 43 days
Series B	1:2:4(v/v);w/c=0.50;slump=0mm 1:2:5:5(v/v);w/c=0.65;slump=0mm 1:3:6(v/v);w/c=0.75;slump=0 1:2:4(v/v);w/c=0.65;slump=10mm 1:2:5:5(v/v);w/c=0.75;slump=12mm 1:3:6(v/v);w/c=0.85;slump=5mm	Full compaction Zero compaction	Air cured Water cured	28 days
Series C	1:2:4(w/w);w/c=0.55;slump=5mm 1:2:4(w/w);w/c=0.70;slump=135mm	Full compaction Zero compaction	Air cured Water cured	28 days

Note: Batching of dry ingredients for (v/v) mixes was done as per ICTAD Specifications (3).

Table 2 - RESULTS OF REGRESSION ANALYSES FOR ULTRASONIC PULSE VELOCITY CORRELATIONS

Model	(A) $f = k_1 V^{m1}$			(B) $f = k_2 e^{m2V}$			(C) $f = k_3 + k_4 N + k_5 V^{m1}$				(D) $f = k_6 + k_7 + k_8 N + k_8 e^{m2V}$			
Parameters	k_1	m_1	r^2	k_2	m_2	r^2	k_3	k_4	k_5	r^2	k_6	k_7	k_8	r^2
Dry Cubes	0.018	4.82	0.92	0.100	1.24	0.93	-8.99	0.664	0.013	0.91	-8.39	0.646	0.067	0.92
Wet Cubes	0.016	4.75	0.88	0.094	1.19	0.90								

FIG 1 - CORRELATION BETWEEN REBOUND NUMBER AND CUBE STRENGTH

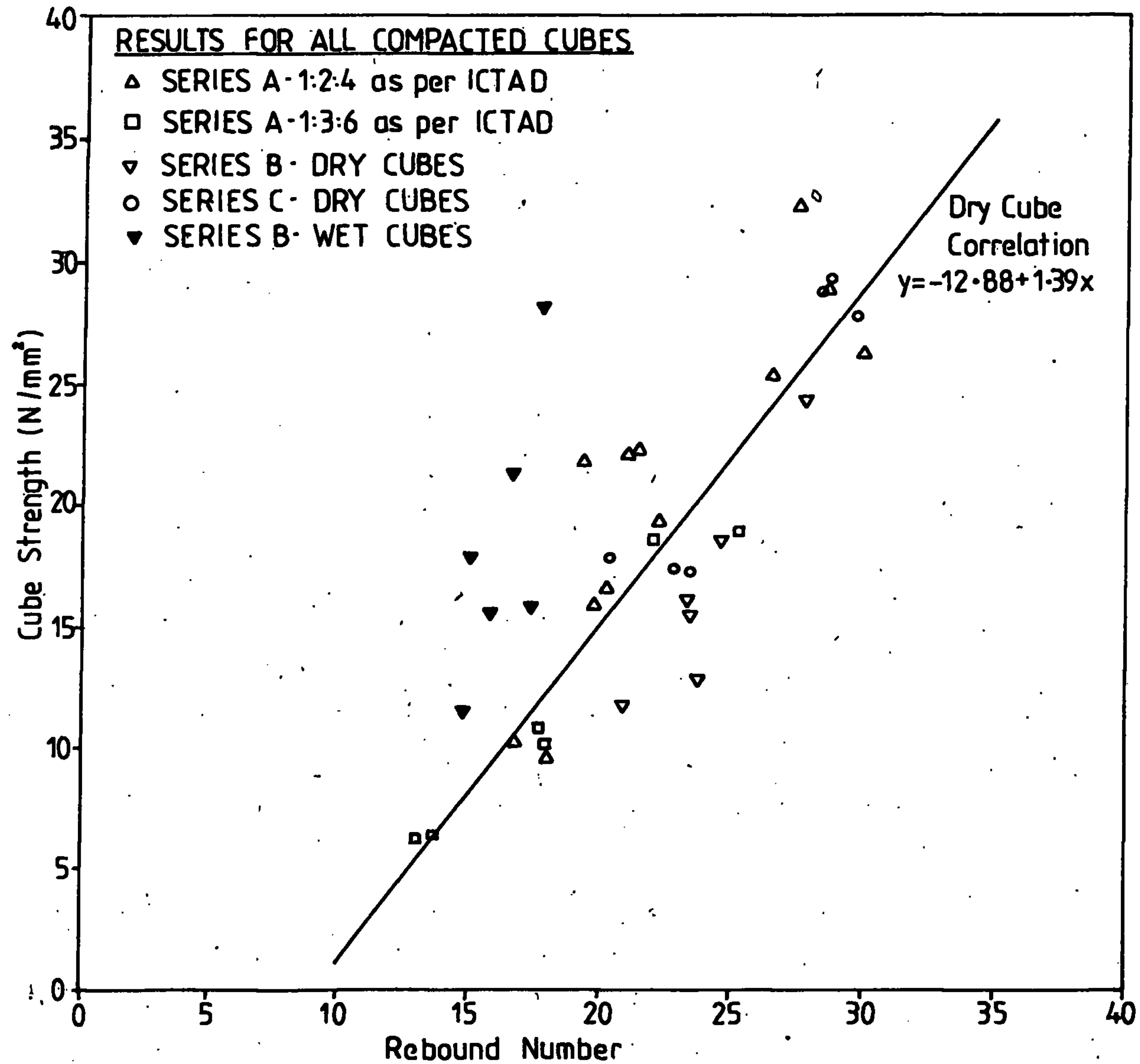

FIG. 2 - PULSE VELOCITY vs CUBE STRENGTH FOR DIFFERENT TYPES OF DRY CUBES

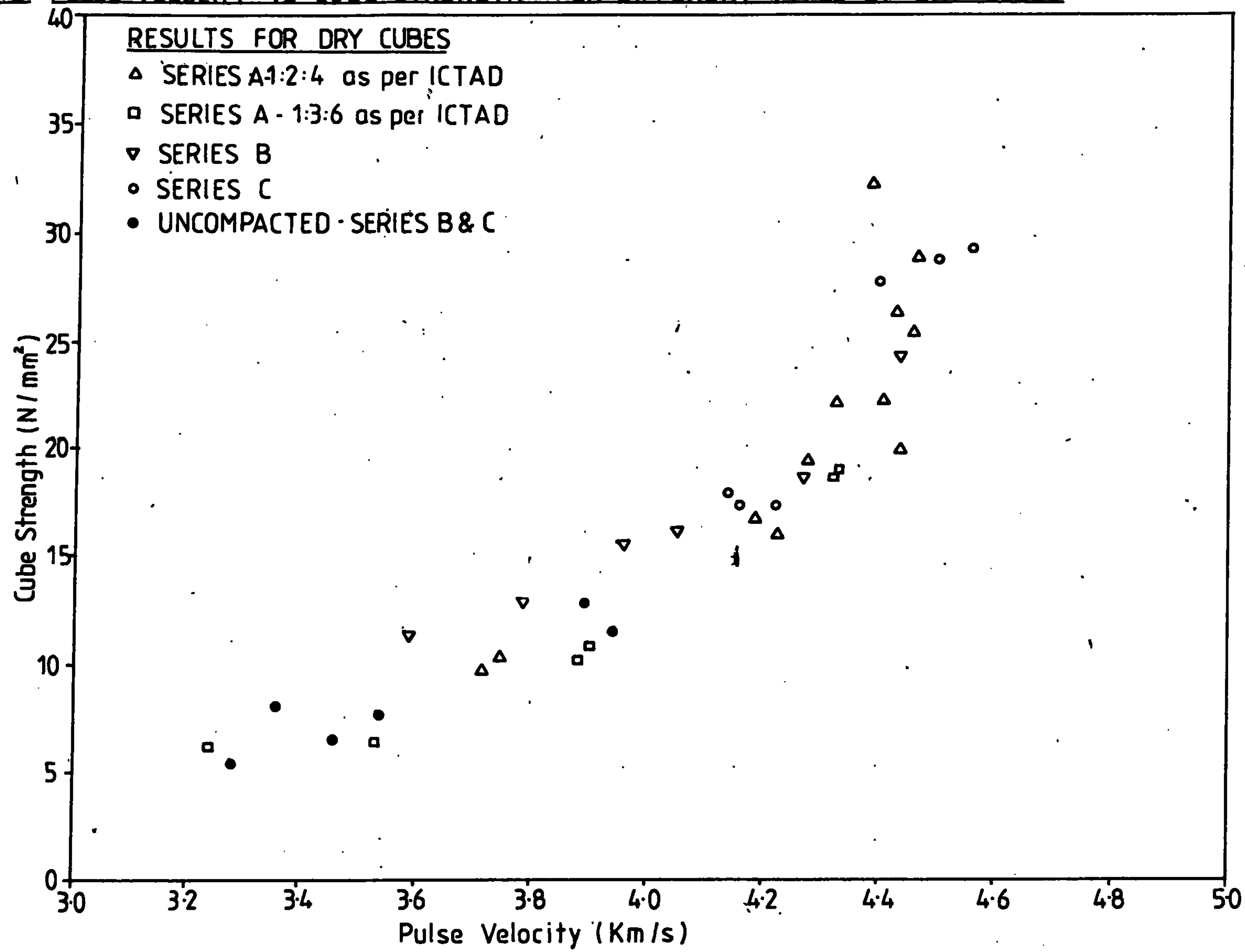

FIG. 3 - PULSE VELOCITY vs. CUBE STRENGTH FOR DRY AND WET CUBES

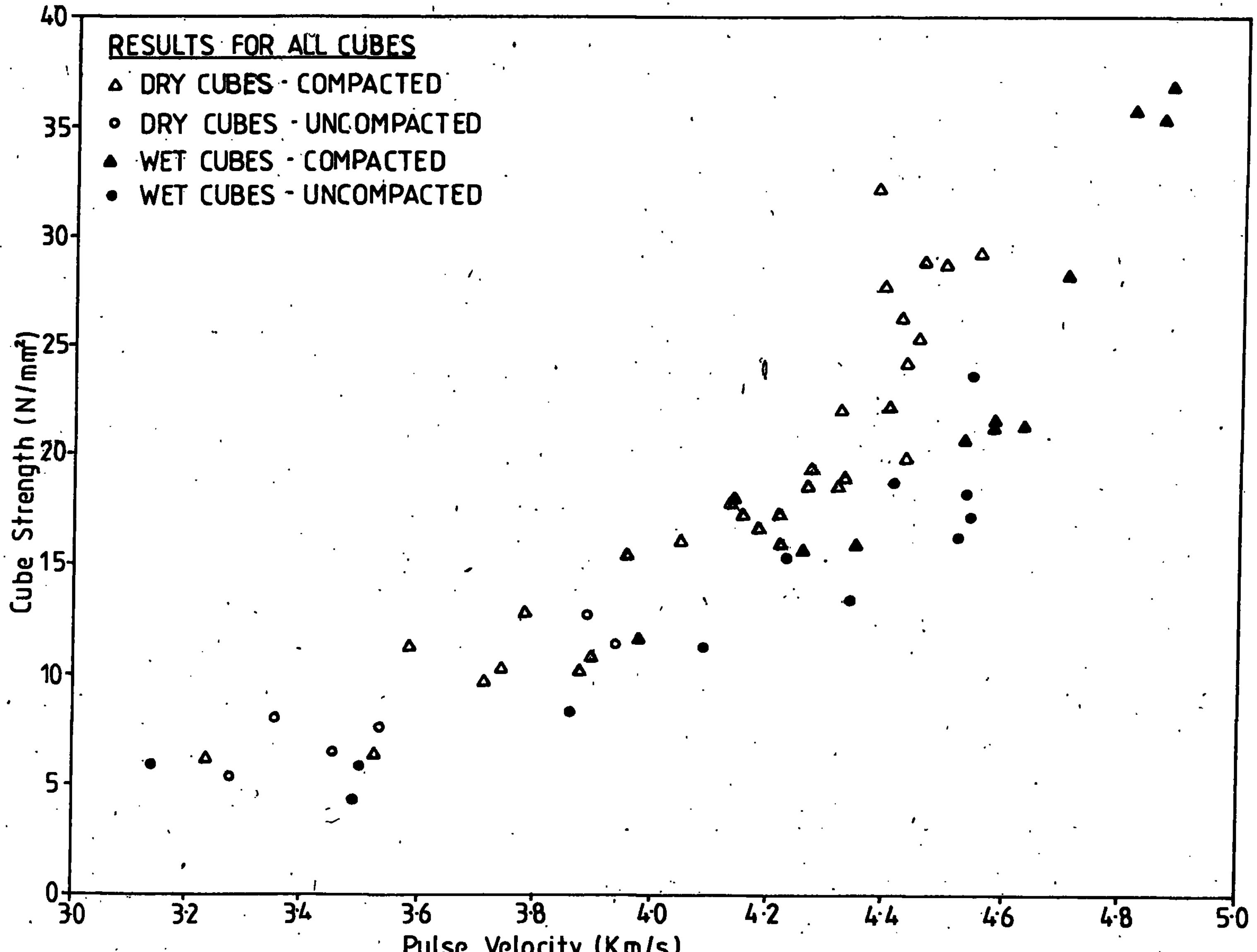

FIG. 4- CORRELATION BETWEEN PULSE VELOCITY AND CUBE STRENGTH

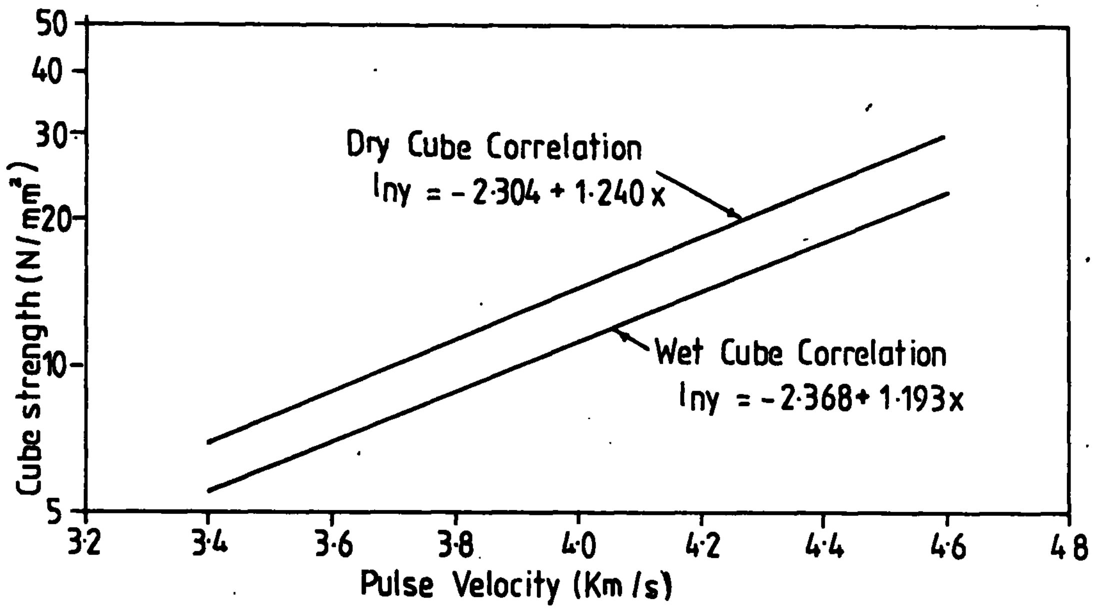

FIG. 5- PULSE VELOCITY vs CUBE STRENGTH FOR WET CUBES AND STRUCTURE