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Effects of Steel on Ultrasonic Measurements for Concrete Members

Effets de l'acier sur les mesures par ultrasons dans les éléments en béton

Einfluss der Bewehrung auf Ultraschallmessungen an Betonelementen

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SUMMARY

Embedded reinforcement may have a significant effect on ultrasonic pulse velocity measurements taken through concrete members. If test locations cannot avoid the influence of reinforcement it is essential that reliable corrections be made. This paper demonstrates that currently accepted allowances are unsatisfactory in practice and confirms that bar diameter is an essential variable to be considered. A correction procedure is proposed which has been developed from the results of laboratory testing.

RESUME

Les barres d'armature peuvent avoir un effet important sur les mesures de vitesse de pulsation ultrasonique au travers d'éléments en béton. Si les emplacements de mesure ne peuvent pas éviter l'influence de l'armature, il est de toute nécessité de faire des corrections sûres. Cet étude démontre que les rectifications couramment acceptées ne sont pas satisfaisantes en pratique et confirme que le diamètre de la barre est une variable essentielle dont il faut tenir compte. Un procédé correctif a été développé à partir des résultats d'expériences.

ZUSAMMENFASSUNG

Eingebettete Bewehrung kann einen grossen Einfluss auf die Ultraschallmessungen an Betonelementen haben. Wenn mittels der Messposition der Einfluss der Bewehrung nicht vermieden werden kann, ist es notwendig, Korrekturen einzuführen. Der Beitrag zeigt, dass die zur Zeit in der Praxis akzeptierten Korrekturfaktoren nicht befriedigend sind und bestätigt, dass der Durchmesser der Bewehrung eine wesentliche Variable ist. Ein aus den Laborversuchen entwickeltes Korrekturverfahren wird vorgeschlagen.

1. INTRODUCTION

1.1 Significance of Reinforcement

It is well established that embedded reinforcement which is located along, or close to, the line of ultrasonic pulse velocity measurements will influence the measured values. This is recognised by National and International Standards which recommend that reinforcement should be avoided whenever possible when selecting test locations. Such an approach is clearly the most reliable. With the aid of cover measurement devices this may often be practicable, but there will also be circumstances in which this proves to be impossible. In these cases it is necessary to make a correction to the measured value to provide an estimate of the velocity of the pulse in the plain concrete. Corrections of this type are not easy to establish because of the nature of the variables involved, and the steel influence may dominate over the concrete properties. This will inevitably reduce the confidence that can be placed in the value obtained, but careful examination of the parameters involved may help to reduce the uncertainty.

1.2 Existing Allowances and their Shortcomings

The current recommendations given by British Standards [1] and RILEM [2] for this are essentially similar and involve only the two basic parameters of concrete pulse velocity and relative pulse path lengths within the steel and concrete. An average pulse velocity through embedded steel (greater than through concrete) is assumed, and factors are given to allow for the maximum possible influence of the steel. In practice it has been suggested [3] that the diameter has a considerable effect on the pulse velocity within the steel bar. This value is further affected by the velocity of a pulse through the concrete surrounding the bar, and the condition of the bond between steel and concrete may also be important. The presence of cracking in the concrete will further complicate the situation.

The use of correction factors which do not allow for these features may result in a significant underestimate of the true pulse velocity within the concrete and lead to subsequent misinterpretation of the test results. This is a major shortcoming of the currently recommended allowances which only provide an indication of the maximum possible effects of reinforcement. These are of limited value, and may be very misleading for practical situations with common bar sizes.

1.3 Aims of Investigation

The results presented in this paper have been obtained in the course of a laboratory investigation to examine the influence of a range of variables upon the effects of embedded steel on pulse velocity measurements. The purpose of the work was to confirm and extend the basic findings of Chung [3] in relation to the currently recommended corrections, and to consider the significance of bond defects and cracking. More realistic correction procedures can thus be identified and their reliability assessed.

2. THEORETICAL BACKGROUND

2.1 Basic Theory

The influence of steel may be of importance whenever it is possible for a pulse to arrive more quickly at the receiving transducer by taking a path passing partly through the steel rather than through the concrete alone. The important features are therefore:-

a) location of reinforcement relative to the transducer positions.
b) pulse velocity within the concrete (V_c km/s).
c) pulse velocity within the steel (V_s km/s).

By reference to Fig. 1 it can be shown that for a bar lying parallel to the proposed path, the steel will potentially influence the results when

$$\frac{a}{L} < \frac{1}{2}\sqrt{\frac{V_s - V_c}{V_s + V_c}}$$

in which case, the pulse velocity in the concrete is given by

$$V_c = \frac{2a\,V_s}{\sqrt{4a^2 + (TV_s - L)^2}} \text{ km/s}$$

provided that $V_s \geq V_c$, where
T = measured transit time (sec.).

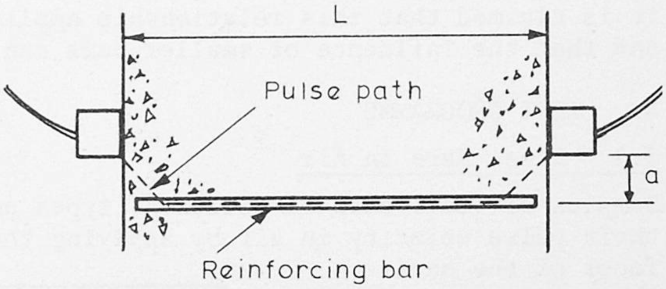

Fig. 1 Influence of longitudinal bar

If the measured pulse velocity in such circumstances is V_m, a correction factor (k) can be developed such that $V_c = kV_m$, with V_s and a/L as variables such that

$$k = \gamma + 2\left(\frac{a}{L}\right)\sqrt{1 - \gamma^2} \quad \text{where } \gamma = \frac{V_c}{V_s}$$

It can be shown that the above expressions will only hold when the offset (a) is large in relation to the end cover (c). If a < 2c (approximately) then the pulse will theoretically pass through the full length of the bar (L_s) and the velocity through concrete is given by:

$$V_c = \frac{2V_s(\sqrt{a^2 + c^2})}{(TV_s - L_s)} \text{ km/s}$$

and for the case where a = 0 (i.e. bars directly in line with pulse) the correction factor k may be obtained from

$$k = 1 - \frac{L_s}{L}(1 - \gamma)$$

This same expression will apply to the case of bars transverse to the pulse path, as shown in Fig. 2, in which case the total path length in the steel (L_s) is taken as the sum of the diameters of the individual bars.

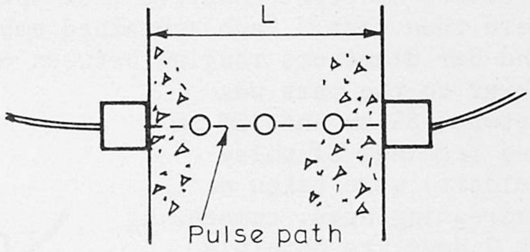

Fig. 2 Transverse bars

The above expressions are based on the assumptions that concrete is a uniform homogenous material, and that the pulse is transferred between the concrete and steel with total efficiency. They also require a value for V_s, the pulse velocity in the steel embedded in the concrete, to be available. Although the value will be influenced by the pulse velocity in the surrounding concrete, no detailed information concerning this is currently available in Standards. B.S. 4408: Pt. 5 [1] provides correction data based on V_s = 5.5 km/s for longitudinal bars.

2.2 Effect of diameter and surrounding concrete

Chung [3] has proposed an effective velocity concept to account for the fact that the pulse velocity in steel varies according to the surrounding medium.

For a bar embedded in concrete, the effective pulse velocity along the bar will be less than for the bar in air and is dependent upon its diameter. Chung has developed the following empirical expression to allow for these combined effects

$$V_s = 5.90 - 10.4(5.9 - V_s)/\Phi \quad \text{where } \Phi \text{ is the bar diameter.}$$

It is claimed that this relationship applies to bars of 10 mm diameter or over, and that the influence of smaller bars can scarcely be detected.

3. TEST PROGRAMME

3.1 Steel Bars in Air

Samples of steel bars of different types and diameters were tested to determine their pulse velocity in air by applying the transducers to the smoothed end faces of the bars. These values are plotted in Fig. 3 for transducers with a frequency of 54 kHz which is the type most commonly used for insitu concrete investigations. Measured values using a frequency of 82 kHz were found to be approximately 2% higher.

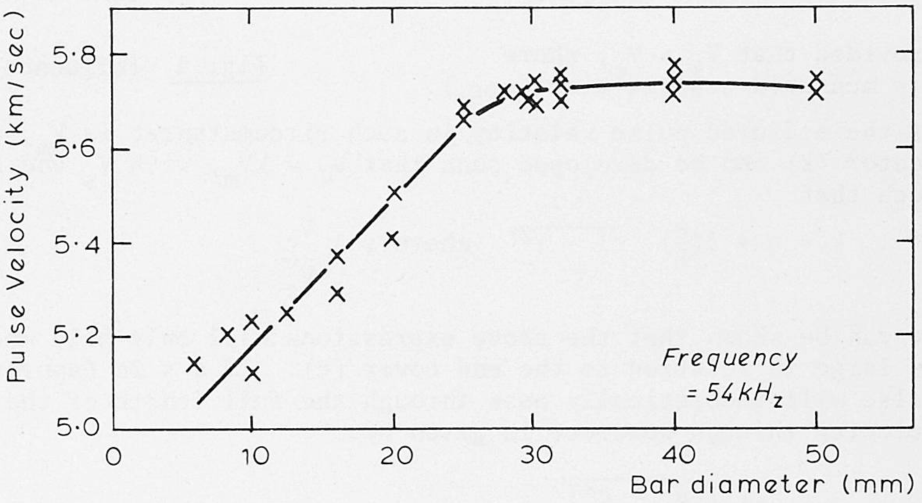

Fig. 3 Results for bars in air

3.2 Steel Bars Embedded in Concrete

A series of eight concrete test specimens with dimensions 490 x 250 x 150 mm were then cast. Each contained embedded reinforcement as shown in Fig. 4, and bar diameters ranging between 6 mm and 50 mm were used. Initially the end cover to the bars was between 85 mm and 130 mm and readings of pulse velocity were taken at increasing ages, commencing at 2 days, to obtain a range of concrete pulse velocities between 3.9 km/s and 4.5 km/s. These measurements were taken directly along the line of each bar, and also transversely across the block in line with each bar. Subsequently the ends of the blocks were sawn off to give end covers in the range 20-25 mm and the longitudinal measurements were then repeated. Round mild steel was generally used since earlier preliminary tests had indicated no significant differences due to steel type, and a pulse velocity of 54 kHz was adopted for these tests.

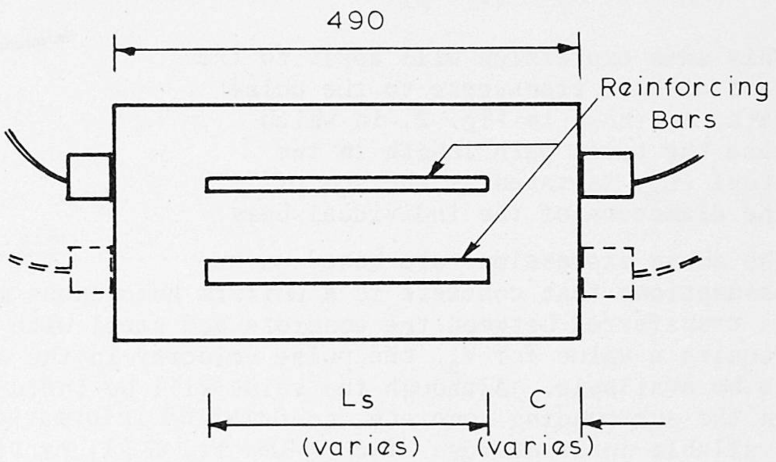

Fig. 4 Test block

3.3 Effects of Cracking and Bond

Following the longitudinal readings with 25-30 mm end cover, a single substantial crack was induced across the full cross-section of each block approximately at the midpoint of its length. The longitudinal readings were then repeated for comparison with the previous values. In addition to two blocks of the series which contained bars liberally coated with grease prior to casting, further specimens in the form of 150 mm cubes were made with comparative greased and ungreased bars cast-in with their ends projecting from the cubes. 10 mm and 32 mm bars were examined in this way.

3.4 Beam containing reinforcement

Following the above tests, an extensive series of readings was taken across the 150 mm width of a 4 m long reinforced concrete beam which had been cast in the laboratory by undergraduate students. Readings were taken at 3 levels, including that of the 12 mm main steel, and were spaced to be in line with, and midway between, the 6 mm links.

4. DISCUSSION OF RESULTS

4.1 Steel Bars in Air

It is clear from Fig. 3 that the pulse velocity along a reinforcing bar in air is reasonably constant for bar diameters of 30 mm and above, with an average value of approximately 5.72 km/s. This reduces with bar diameter below that size in an approximately linear manner.

4.2 Embedded bars parallel to pulse path

The effective velocity in each reinforcing bar has been calculated from the measured values by allowing for the concrete end cover and γ evaluated. Comparisons of the results with established theories are summarised in Fig. 5 which shows the ratio of theoretical/measured velocities in the steel for concrete pulse velocities between 4 km/s and 4.5 km/s. This covers the most commonly occurring range of concrete quality and indicates that the experimental values of V_S generally agree with Chung's predictions for bars of 20 mm diameter or over. For smaller bars, Chung's theory underestimates the steel influence and his contention that bars of 10 mm or less may be ignored is not confirmed.

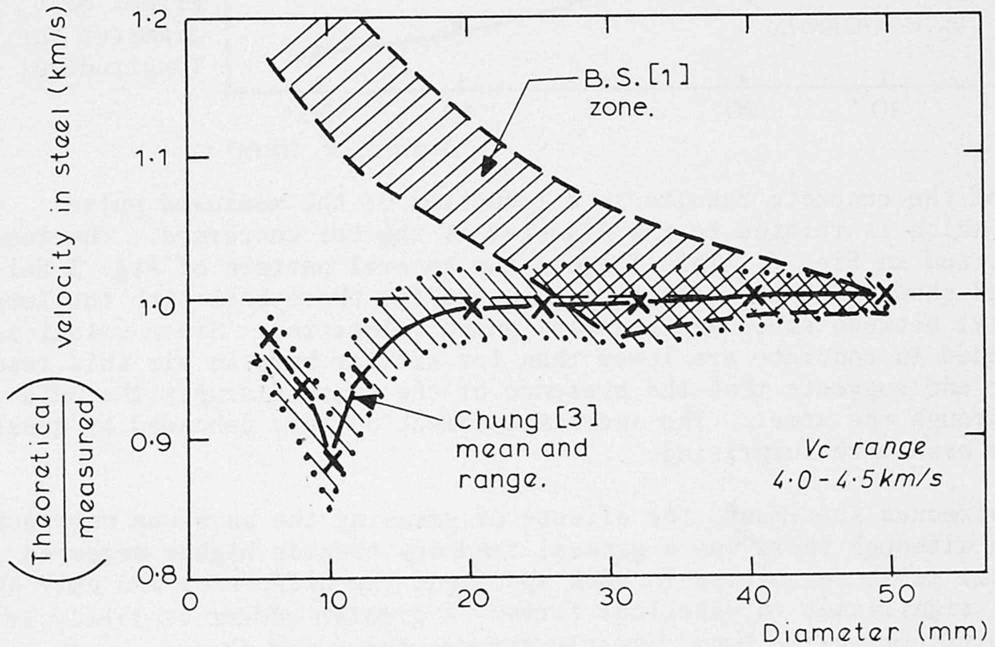

Fig. 5 Results for longitudinal bars

The British Standard values provide a broad band for the range of V_c since V_s is assumed to be constant. The prediction is good for 50 mm bars, and remains reasonable for bars of 30 mm or over in good quality concrete. Below this size it has been shown (Fig. 3) that the bar velocity decreases significantly, and this corresponds well with the features of Fig. 5, which demonstrates the inadequacy of the currently accepted corrections.

The overall range of measured values was approximately 5% for any particular combination but it must be remembered that the generally accepted accuracy of measured pulse velocities on a concrete member is about ± 2%. It was found that the measurements with reduced end cover to the bars yielded higher apparent steel pulse velocities (2% to 3% on average) than those for larger end covers. This may be due to reduced pulse attenuation within the cover concrete, but the influence of differences in contact surface (moulded and sawn) may also have contributed. It should be noted that Chung [3] used 32 mm end cover with moulded contact surfaces.

Measured values of γ are plotted in Fig. 6 for two levels of concrete pulse velocity, and may be used as the basis of a correction factor when used in conjunction with the expression given in section 2.1. The importance of bar diameter is clear, and it will be noted that for small diameter bars the velocity of pulses in the surrounding concrete is of reduced significance. It is also clear that bars of only 6 mm diameter may be detected although their effect is small, and the links of this size could not be identified in the tests on the beam when V_c = 4.4 km/s and $L_s \approx 0.67L$.

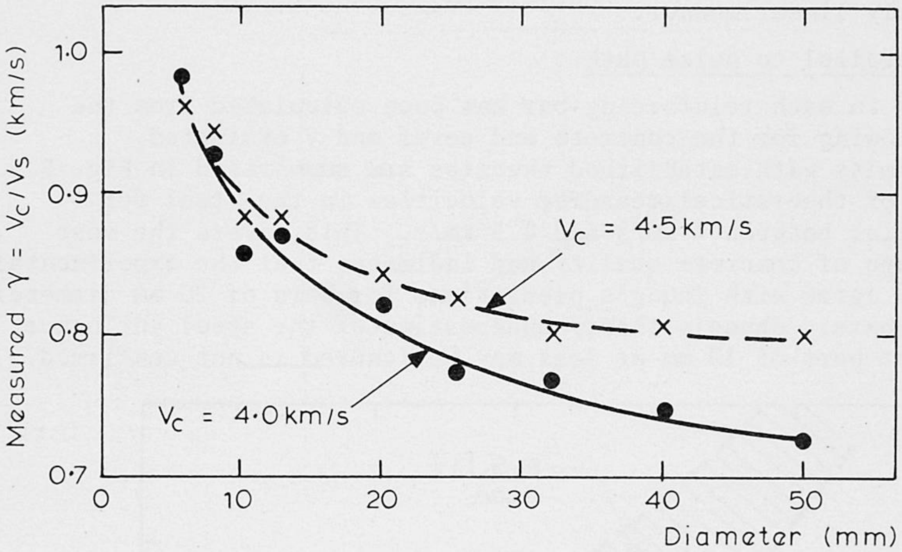

Fig. 6
Effect of V_c and diameter for longitudinal bars

Cracking of the concrete results in a reduction of the measured pulse velocity, which is related to the diameter of the bar concerned. The results are summarised in Fig. 7. This follows the general pattern of Fig. 3 for bars in air, and shows that the effect is greatest for those bars with the largest differential between steel and concrete pulse velocities. Since velocities in bars embedded in concrete are lower than for similar bars in air this result is surprising and suggests that the presence of the crack disrupts the pulse passing through the steel. The increased effect on bars debonded by greasing is perhaps even more surprising.

For the uncracked specimens, the effects of greasing the bars was unexpectedly small, and although there was a general tendency towards higher measured longitudinal pulse velocities in such specimens the difference was only about 1% and not significant in practical terms. A greater effect is likely if the pulse does not enter the bars directly through these end faces.

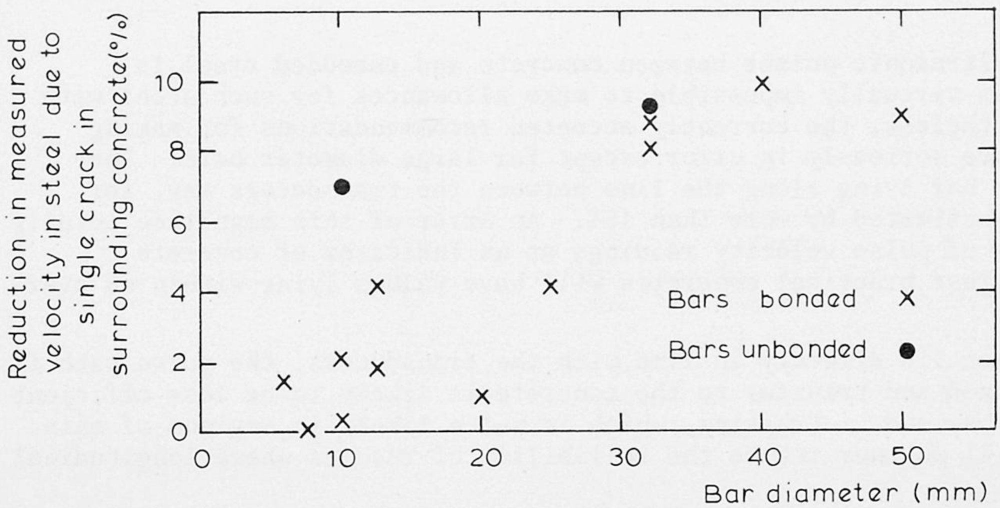

Fig. 7
Effects of cracking

4.3 Transverse Bars

Calculated effective pulse velocities in the steel yield values of low accuracy due to the small path in steel. Consequently, these results have been presented directly in the form of the correction factor k required to convert measured pulse velocity to concrete pulse velocity. For ease of presentation, the values corresponding to $L_S/L = 0.2$ have been computed from the measured readings and are plotted in Fig. 8 for two values of concrete pulse velocity.

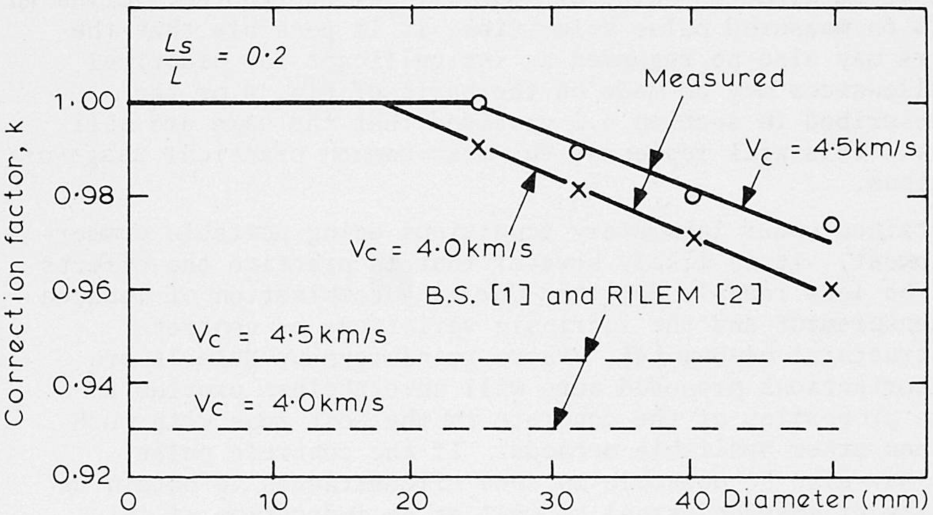

Fig. 8
Correction factors for transverse bars

The inadequacy of existing recommended corrections is again obvious. The effect of reinforcement in this orientation is much smaller than longitudinally, but is nevertheless related to the bar diameter with bars of 20 mm or smaller scarcely detectable. Tests on the beam (section 3.4) showed no influence from the 12 mm main bars. Earlier tests by the Author [4] have indicated that a theoretical estimate of the effect of a transverse bar may be obtained by consideration of the bar as having an equivalent longitudinal length equal to the diameter, but with an effective diameter equal to one half of the true value. Use of the expression proposed by Chung [3] will then yield a value of V_S and hence correction factor k. If this approach is applied to this series of tests, excellent agreement is obtained with the measured values.

The effect of greasing on transverse readings was found to be dramatic, with the result that the influence of the bar disappeared completely. The pulse in this situation is unable to effectively enter the steel, which becomes equivalent to a void of insufficient size to be detected.

5. CONCLUSIONS

The transfer of ultrasonic pulses between concrete and embedded steel is complex, and it is virtually impossible to make allowances for such steel with precision. Nevertheless, the currently accepted recommendations for making such allowances are seriously in error except for large diameter bars. The effect of a 10 mm bar lying along the line between the transducers may, for example, be over-estimated by more than 15%. An error of this magnitude totally negates the value of pulse velocity readings as an indicator of concrete properties since most practical concretes will have values lying within an overall range of 20%.

If the bar does not lie directly in line with the transducers, the pulse path is less clearly defined and transfer to the concrete is likely to be less efficient than through the bar ends. Cracking, which is quite likely in regions of main reinforcement, will further reduce the reliability of results where longitudinal steel is present.

Small diameter bars, such as those commonly used for links and binders may have a significant influence, and where longitudinal steel cannot be avoided it may be allowed for by the use of Fig. 6 to obtain a suitable correction factor. An estimate of concrete pulse velocity obtained in this way may be expected to be accurate within ± 3% provided that cracking is not present and precise details of the steel are known.

Transverse steel has been found to have a much smaller effect than predicted by existing methods, and 20 mm diameter bars, or smaller, may be ignored. Given an accepted error of ± 2% on measured pulse velocities, it is possible that the influence of 25 mm bars may also be regarded as insignificant for practical purposes. Reliable allowances may be made on the basis of Fig. 8 or the numerical procedure described in section 4.3 provided that the bars are well bonded to the concrete. This will represent the most common practical usage of reinforcement corrections.

These results were obtained under laboratory conditions using portable commercially available equipment. It is likely however that in practice the effects of reinforcement will be less readily detected due to a combination of reduced accuracy of on-site measurement and the intrinsic variations of concrete properties within a structural member [4]. Where reinforcement details are known the use of the corrections proposed here will nevertheless provide an indication of the true properties of the concrete in the test zone with much greater reliability than other available methods. If the concrete pulse velocity is known, it may also be possible in some circumstances to obtain an estimate of the quantity of embedded steel as well as an indication of its presence.

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