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ULTRASONIC PULSE VELOCITY (UPV) IN CONCRETE UNDER COMPRESSION: A STUDY ON EFFECT OF ASPECT RATIO

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ULTRASONIC PULSE VELOCITY IN CONCRETE UNDER COMPRESION: A STUDY ON EFFECT OF ASPECT RATIO

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Abstract

This paper describes a research study on the effect of aspect ratio in concrete at different levels of compressive stress using the measurement of ultrasonic pulse velocity (UPV) values. Grade 25 and 30 concrete prisms with different height/width ratio were used and tests were carried out at the ages of 7 and 28 days. Test results at the ages of 7 days and 28 days were found to have similar representation. In general, the UPV values increase in concrete prisms at stress-strength ratio ranging from 0 to 5%. It was found that compressive stress in concrete at stress-strength ratio of about 10% have more significant effect of the measured UPV values on Type I prism with the smallest height/width ratio. Concrete prisms at the age of 7 days are subjected to more significant changes of UPV values compared to concrete of same grade at the age of 28 days. However the changes of UPV values in grade 30 concrete are less significant than grade 25 concrete. The changes of measured UPV values at the mid height of concrete prisms are more significant than the ends. Even though prism with the smallest height/width ratio is showing the most significant changes of UPV values for most of the increment and reduction condition when the stress is increased to 10%, the reduction of UPV values occurs at higher stress-strength ratio. The greatest change of 8.7% during the reduction of UPV values at the mid height of concrete prisms is recorded on Type IV prism with the largest height to width ratio of grade 25 concrete at 7 days.

Abstrak

Kertas kerja ini merupakan penyelidikan tentang kesan dari segi nisbah dalam konkrit pada tahap tegasan mampatan yang berlainan dengan menggunakan "Ultrasonic Pulse Velocity" (UPV). Prisma pada gred konkrit 25 dan 30 pada nisbah ketinggian kepada lebar yang berlainan digunakan. Eksperimen ini dijalankan apabila konkrit sampel mencapai 7 dan 28 hari. Keputusan bagi konkrit pada hari ke-7 adalah serupa dengan konkrit pada hari ke-28. Secara umumnya, nilai bagi UPV meningkat apabila kadar tegasan-kekuatan berada dalam lingkungan 0 hingga 5%. Didapati bahawa tegasan mampatan dalam konkrit pada kadar tegasan-kekuatan 10% mempunyai kesan yang lebih berpengaruh terhadap nilai UPV yang diukur pada prisma Jenis I yang mempunyai nisbah ketinggian kepada lebar yang paling kecil. Perubahan nilai UPV terhadap prisma konkrit pada hari ke-7 adalah lebih besar jika dibandingkan dengan konkrit gred yang sama pada hari ke-28. Walau bagaimanapun, perubahan nilai UPV dalam konkrit gred 30 adalah lebih besar dibandingkan dengan konkrit gred 25. Perubahan dalam nilai-nilai UPV yang diukur adalah lebih besar pada pertengahan ketinggian prisma konkrit jika dibandingkan dengan kedua-dua hujung tersebut. Walaupun, prisma konkrit yang mempunyai nisbah ketinggian kepada lebar yang terkecil menunjukkan perubahan yang lebih besar dalam perubahan nilai-nilai UPV dalam kebanyakan situasi yang meningkat dan menurun semasa tegasan dipertingkatkan kepada 10%, peruhahan dalam nilai-nilai perubahan UPV berlaku pada kadar tegasan-kekuatan yang lebih tinggi. Perubahan nilai UPV yang terbesar adalah sebanyak 8.7% semasa nilainya menunjukkan penurunan pada pertengahan ketinggian prisma konkri gred 25 Jenis IV yang mempunyai nisbah ketinggian kepada lebar terbesar yang mencapai hari ke-7.

Table of Contents

Contents		Page

List of Tables

List of Figures

List of Symbols

L	-	Path length
t	-	Time traveled by Ultrasonic Pulse
V	-	Velocity of ultrasound in concrete
E_d	-	Elastic modulus
ρ	-	Density of material
μ	-	Poisson's ratio

Chapter 1: Introduction

1.1 General

The quality of concrete is usually taken to mean its compressive strength and durability although other properties such as resistance to deformation and shrinkage can be significant in determining structural behavior. In recent years, there has been proliferation of the use of nondestructive test (NDT) methods to determine strength, physical properties and condition of hardened concrete. NDT methods are relatively simple to apply and do not cause any significant damage to concrete members, therefore their applications are preferred over full-scale load and destructive tests.

Since the compressive failure of concrete is usually caused by the formation of cracks, the size effect of specimen has to be implemented. Even though the behavior of compressive failure has been studied extensively, the failure mechanism and its size effect have been insufficiently studied when compared to tensile failure mechanism.

Ultrasonic pulse velocity (UPV) method is one of the most important applications for checking the uniformity of concrete and monitoring the changes in a concrete with time. Strength estimation is possible within ± 20% accuracy, which can only be achieved under strict laboratory conditions. The other applications (defect detection, crack depth measurements, and so forth) are even less reliable. Thus, they are inadequate for practical purposes, especially under field conditions.

The lowering of density caused by an increase in water cement ratio or by poor compaction causes both a lowering in strength of the concrete and a reduction in the velocity of a pulse of ultrasound transmitted through it. Furthermore, the presence of voids across the path of the sound causes diffraction of the pulse and thus a reduction in its velocity.

In this final year project, the effect of aspect ratio of concrete specimen is considered when estimating the compressive strength of a concrete at various loading conditions. The ratio of height to width of concrete prism will be tested for both concrete grades 25 and 30.

Several laboratory equipments such as crushing machine, Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT), and test frame (MECHON SE 100) are utilized to study the effect of aspect ratio of concrete specimen. From the experimental data, the relation between the effect of aspect ratio of concrete specimen and ultrasonic pulse velocity can be clarified on graphs.

1.2 Objective

The main objective of this project is to study the effect of aspect ratio in concrete at different levels of compressive stress using the measurement of ultrasonic pulse velocity.

1.3 Scope of work

The scope of work in this study includes

(i) Preparing concrete cubes and prisms with the different height to width for the compression tests

(ii) Direct measurement of UPV using Portable Ultrasonic Nondestructive Digital Indicating Tester (PUNDIT) for concrete prisms under compression.

Chapter 2: Literature Review

2.1 General

This chapter describes a review on ultrasonic pulse velocity (UPV), compressive strength of concrete, size effect to compressive strength of concrete, and the effect of UPV to the compressive strength of concrete.

2.2 Ultrasonic Pulse Velocity

Ultrasonic waves or stress waves are utilized in the measurement of Ultrasonic Pulse Velocity (UPV) in order to evaluate the concrete quality in structures. Unlike other forms of electromagnetic radiation, which can travel freely through vacuum, ultrasonic waves can only exist within mass media. The waves are transmitted from one mass to another by direct and intimate contact between the masses.

The measurement of ultrasonic pulse velocity will require apparatus that include a transmitting transducer and receiving transducer to transmit ultrasonic waves (frequency ranging from 10 to 150 kHz is used for testing of concrete) directly through concrete specimen. It measures the path length and time of travel of an ultrasonic pulse passing through the concrete.

Generally a denser material will have faster velocity. With the path length (L) and the time travel (t) an ultrasonic pulse obtained using the instrument and hence the Ultrasonic Pulse Velocity (UPV) in the specimen can be calculated by the following equation:

$$UPV = \frac{L}{t} \tag{2.1}$$

2.3 Compressive Strength of Concrete

The compressive strength of concrete is taken as the maximum compressive load that it can carry per unit area. Concrete strengths of up to 120 Nmm^{-2} can be achieved by selective use of type of cement, mix proportions, method of compaction and curing conditions.

Concrete members are normally designed on the basis that concrete is capable of resisting only compression, the tension being carried by steel reinforcement. A 150 mm cube is commonly used for determining the compressive strength.

The standard method described in BS 1881: Part 116 requires that the test specimen should be cured in water at 20 ± 2 °C and crushed by loading it at a constant rate of stress increase of between 12 and 24 Nmm^{-2} min^{-1} immediately after it has been removed from the curing tank.

2.4 Size Effect to Compressive Strength of Concrete

The compressive strength of laboratory size specimens differ from that of larger structural members used in construction of real structures. The difference in the compressive strength is a direct consequence of energy release into a finite-size fracture process zone.

In the early 1980's, it became clear that the size effect on the compressive strength of concrete failing after large stable crack growth is caused principally by energy release (BaMzant and Xi 1991) and cannot be explained by Weibull-type statistics of random micro-defects. Ever since, the problem of size effect has received increasing attention (BaMzant and Chen, 1997). Energy analysis of fracture mechanics type is required in order to describe the size effect.

Most concrete structural members experience combined loading conditions composed of compression, tension, moment, and shear. Especially, in the case of reinforced concrete members, the fundamental idea of concrete resisting compressive stress and steel resisting tensile stress is the basic foundation of reinforced concrete structural design.

Fracture mechanics-based formulation of size effect theory has not been studied rigorously for compression-loaded members. It was experimentally shown that the ratio of the compressive failure stress to the compressive strength decreases as the specimen size increases.

This phenomenon of reduction in strength dependent on specimen size is called the "reduction phenomenon". Due to the fracture mechanics-based derivation of size effect law, however, earlier researchers have focused more on pure tension and shear loading conditions rather than compressive loading condition. Only recently, studies (Cotterell, 1972, Jenq and Shah, 1991) on compressive loading based size effect became a focus of interest among researchers.

Currently, researchers in the field accept the conclusion that the failure of concrete loaded in tension is caused by strain localization resulting in a finite size fracture process zone (FPZ). In the last few years, many researchers (BaMzant, 1989, Vonk, 1992) have started to realize that the strain localization also occurs for concrete specimens loaded in compression. Unlike failure caused by pure tension loading which usually takes place in a relatively narrow localized zone, compressive loading failure occurs within a larger damage zone.

The compressive failure shows a similar failure mechanism as tensile failure. In both cases, failure is caused by the distribution of the splitting cracks in the direction of member length as the lateral deformation increases during failure progression. However, the compressive failure mechanism is more complex than tensile failure mechanism. Size effect of compressive failure is not as distinct as in tensile failure, because the formation of microcracks in compressive failure is distributed in a wider region than in tensile failure.

The failure mechanism and the size effect have been insufficiently studied even though the behavior of compressive failure has been studied extensively. However, endeavouring studies by some researchers have continuously expanded knowledge in the field. Experimental data for proper analyses of size effect is correctly lacking however. From the few available experimental data, it is apparent that compressive strength decreases as specimen sizes increase.

2.5 Ultrasonic Pulse Velocity to The Compressive Strength of Concrete

Ultrasonic Pulse Velocity method is based on the fact that the velocity, V of ultrasound in a concrete is related to the elastic modulus E_d by the expression where ρ is the density of the material and μ, poisson's ratio, that is,

$$V^2 = \frac{E_d(1-\mu)}{\rho(1+\mu)(1-2\mu)} \tag{2.2}$$

Equation (2.2) may be considered to apply to the transmission of longitudinal pulses through a solid of any shape or size provided the least lateral dimension (that is, the dimension measured perpendicular to the path traveled by the pulse) is not less than the wavelength of the pulse vibrations. The pulse velocity is not affected by the frequency of the pulse so that the wavelength of the pulse vibrations is inversely proportional to this frequency.

Since the pulse velocity depends only on the elastic properties of the material and not on the geometry, this is a very convenient technique for evaluating concrete quality. The British Standards Institution has issued Recommendations for measurement of velocity of ultrasonic pulses in concrete. B.S. 1881: Part 203: 1986.

The velocity of ultrasonic pulse passing through concrete is the outcome of the time taken by the pulse to travel through the hardened cement paste and through the aggregate. Even though there is no physical relation between the ultrasonic pulse velocity and compressive strength of concrete, the velocity is related to the changes in hardened cement paste, such as changes in water/cement ratio which affects the modulus elasticity of the hardened cement paste as shown on expression above.

The ultrasonic pulse velocity can only be used to assess the strength of concrete within these limitations. However, pulse velocity travels faster through a water-filled void than through air-filled one. It is normally accepted that a concrete made with ordinary Portland cement and kept in normal curing conditions will develop about 75 per cent of its final strength in the first 28 days. The gain in strength with age up to the time of loading can now be used only for estimating that static modulus of elasticity of concrete in structures.

The lowering of density caused by an increase in water cement ratio or by poor compaction causes both a lowering in strength of the concrete and a reduction in the velocity of a pulse of ultrasound transmitted through it. Furthermore, the presence of voids across the path of the sound causes diffraction of the pulse and thus a reduction in its velocity.

The pulse velocity also depend on the path length, decreasing somewhat as the path length is increased. The pulse velocity is not sensitive to temperature in the range 5 to 30°C. At higher temperatures, the pulse velocity is decreased, and at temperatures below freezing, it is increased. The presence of steel bars will tend to increase the pulse velocity.

In fact, there are three types of waves: longitudinal (compression), shear (transverse) and surface (Rayleigh) generated by pulse generation when it is applied to concrete. The longitudinal waves are the fastest and they are the one that are most useful for testing purposes.

Ultrasonic pulse velocity may used directly as a quality control measure for concrete, but it is more commonly related with compressive strength. Ultrasonic pulse velocity can be measured in several configurations such as direct, semi-direct and indirect transmission, although direct transmission seems to give better results.

2.6 Effect of Compressive Strength on Ultrasonic Pulse Velocity in Concrete

The research study on the effect of compressive strength in concrete using the measurement of ultrasonic pulse velocity (UPV) was carried out by Ngu (2003). In this study, concrete cubes with compressive strength from 25 to 40 MPa were tested at the ages of 7 days and 28 days.

Test results at the ages of 7 days and 28 days have same representation. Ngu (2003) has experimentally shown that the measurement UPV values of the cubes increased by 1 to 2 % under compressive stress of 10 % stress-strength ratio.

Chapter 3: Methodology

3.1 General

This chapter describes the review on measurement of ultrasonic pulse velocity (UPV), utilization of Portable Ultrasonic Nondestructive Digital Indicating Tester (PUNDIT) and test load frame, and preparation of concrete cubes and prisms for the compression tests.

3.2 Ultrasonic Pulse Velocity Method

The method of an ultrasonic pulse passing through the concrete based on BS 1881 : Part 203 is used in this study. This technique is now widely used for assessing the quality of concrete in structures and several models of the apparatus are commercially available.

The pulse, produced by an electro-acoustical transducer is placed in contact with concrete under test, passes through the concrete and received and converted into an electrical signal by a second electro-acoustical transducer. The time taken by the pulse to travel through the concrete is measured by an electrical timing unit to the nearest $0.1\,\mu s$, and the pulse velocity V, is calculated using the relationship of equation (2.1). The accuracy of the velocity thus obtained depends on the length of the path although after a certain length the sharpness of the signal decreases and there is no further gain in the accuracy of the measurement.

In most of the applications it is necessary to measure the pulse velocity too high degree of accuracy since relatively small changes in pulse velocity usually reflect relatively large changes in the condition of the concrete. For this reason it is important that extra care be taken to obtain the highest possible accuracy of both the transit time and the path length measurements since the pulse velocity measurement depends on both of these.

It is desirable to measure pulse velocity to within an accuracy of ± 2% which allows a tolerance in the separate measurements of path length and transit time of only a little more than ± 1%.

In fact, the accuracy of path length measurement is difficult or impossible; an estimate of the limits of accuracy of the actual measurements should be recorded with the results so that the reliability of the pulse velocity measurements can be assessed. Accuracy of transit time measurement can only be assured if good acoustic coupling between the transducer face and the concrete surface can be achieved.

For a concrete surface formed by casting against steel, a good coupling can readily be obtained if the surface is free from dust and grit and covered with a light or medium grease or other suitable couplant. A wet surface presents no problem.

Stiffer grease should be used if the surface is moderately rough but very rough surfaces require more elaborate preparation. In such cases the surface should be ground flat over an area large enough to accommodate the transducer face or this area may be filled to a level smooth surface with a minimum thickness of a suitable material such as plaster of Paris, cement mortar or epoxy resin, a suitable time being allowed to elapse for the filling material to harden.

If the value of the transit time displayed remains constant to within ±1% when the transducers are applied and reapplied to the concrete surface, it is a good indication that satisfactory coupling has been achieved.

Three alternative arrangements for the transducers when testing concrete are shown in Figure 3.1. Whenever possible, the direct transmission arrangement should be used. The arrangement is most accurate in direct transmission mode, where the transmitter and receiver are placed directly opposite each other on parallel faces of the test piece, and the path length can be measured or calculated with a high degree of accuracy. This will give maximum sensitivity and provide a well defined path length.

It is sometimes required to examine the concrete by using diagonal paths and semi-direct arrangements are suitable for these. A lesser degree of accuracy is achieved when the test is applied on mutually perpendicular faces of the test piece, such as at a corner, due to the uncertainty of the true contact point. This is known as semi-direct_transmission

The method is least accurate when both transducers are applied to the same face of the test piece, or indirect transmission. The indirect arrangement is the least satisfactory because, apart from its relative insensitivity, it gives pulse velocity measurements which are usually influenced by the concrete layer near the surface and this layer may not be representative of the concrete in deeper layers. Also, the inaccuracy will be proportionally greater for shorter transmission path than for longer ones. Furthermore the length of the path is less well defined and it is not satisfactory to take this as the distance from centre to centre of the transducers.

The main advantages of the ultrasonic pulse method are that it can be employed for assessing the quality of concrete in structures and there are no restrictions concerning the shape of the concrete mass although access to the structures from both sides is desirable.