PII:S0958-9465(95)00008-X

Cement & Concrete Composites **18** (1996) 119–124
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0958-9465/96/$15.00

Ultrasonic Evaluation of Cement Adhesion in Wall Tiles

K. S. Tan, K. C. Chan, B. S. Wong & L. W. Guan[a]

School of Mechanical and Production Engineering, Nanyang Technological University, Nanyang Avenue, Singapore 2263
[a]School of Civil and Structural Engineering Nanyang Technological University, Nanyang Avenue, Singapore 2263

(Received 27 March 1995; accepted 20 December 1995)

Abstract

Ultrasound is used to evaluate adhesion in tiled wall systems by measuring the signal amplitude of the ultrasound through the media. Portland cement is used as the adhesive with water–cement ratio ranging from 0·3 to 2 by weight. The different water–cement ratio is found to influence the quality of bonding of tile to concrete substrate. The signal amplitude reflected from the tile–cement interface shows that high signal amplitude indicates bonds with very high or very low water–cement ratios. This is taken as poor bonding because the value of this signal amplitude approaches the signal amplitude from an unbonded tile back. The difference in signal amplitude between poor and good bonds is about 1·9 times or 5·6dB. A water–cement ratio of 0·5 to 0·6 is found to have the optimum bonding strength (low signal amplitude). This is confirmed by the pull-off test done on the bonded tiles, where the difference between good and bad bond is about 1·9MN/m^2. The elastic modulus of the cement, as determined from ultrasonic measurements, decreases asymptotically with increasing water–cement ratio. A low water–cement ratio of 0·3 attained the highest value of 4·12GPa. This does not correlate with the pull-off test. Copyright © 1996 Elsevier Science Ltd.

INTRODUCTION

The installation of tiles on wall imparts both durability and aesthetic appeal to the facade of high-rise buildings, and hence it has been a favourite choice for building owners in affluent cities throughout the world. Defective tiled walls, however, are potentially hazardous to pedestrians walking around the building due to falling tiles. For instance, a piece of tile weighing 250g may gain a momentum of 60Nm when it falls from the 10th storey of a building. As newly tiled walls normally look perfect to the naked eyes, non-destructive assessments (NDAs) need to be relied upon as a quality control and regular maintenance procedure. The ultrasonic technique, owing to its ability to gather quantitative information from the building element under investigation, can be employed to complement other fast scanning NDAs, e.g. infrared thermography.

This paper focuses on the ultrasonic technique for detecting and evaluating bonding quality in tiled-wall systems. Poor bonding quality could be caused by improper installation or induced by the differential movement due to mechanical and/or thermal expansion and contraction of adhesives. Some fundamentals of wave theory are highlighted to explain the concepts on which the experimental procedure is based. This is then followed by the description of the experiment which forms part of an ongoing research project on the performance of tiled-wall systems. Experimental results are then discussed.

ULTRASONIC TESTING

One of the typical ultrasonic techniques is the pulse–echo method that uses a single piezoelec-

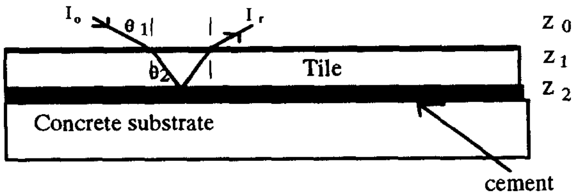

Fig. 1. Schematic diagram of incidence reflection and refraction of an ultrasonic wave at interfaces in a layered system.

tric probe as both transmitter and receiver.[1] The received amplitude of the echoes, from the reflection of the incident ultrasonic wave at an interface, can be used to gauge the strength of adhesion between the two adherent materials.[2] Figure 1 shows the reflection and refraction of the ultrasonic waves at various interfaces inside a layered structure comprising tile and cement, together with an underlying substrate. The cement is the adhesive used to bond the tile to the concrete substrate. Cement in this context refers to the portland cement mixed with water.

Under a normal incidence, i.e. $\theta_1 = 0$, the intensities of the incident wave I_o and the reflected wave I_r, at the interface between the tile and cement, can be related thus:

$$I_r = I_o(1-R_0)^2 R e^{-i[(k+i\alpha)x-\omega t]} \tag{1}$$

where the reflection coefficients at the interfaces (see Fig. 1) are

$$R_0 = \left(\frac{Z_0-Z_1}{Z_1+Z_0}\right) \text{and } R = \left(\frac{Z_2-Z_1}{Z_2+Z_1}\right) \tag{2}$$

The complex term $e^{-i[(k+i\alpha)x-\omega t]}$ represents a unit waveform propagating in the x-direction through the material with α being its attenuation coefficient. Here the transmission coefficient at the interface can be expressed as

$$T = \frac{2Z_2}{Z_1+Z_2} = 1-|R|. \tag{3}$$

In eqns (2) and (3), Z_o, Z_1 and Z_2, are the acoustic impedances of the couplant, tile and cement, respectively. An acoustic impedance Z is a material properly that relates to density ρ, and wave velocity v, i.e. $Z = \rho v$.

Physically, a small difference between Z_1 and Z_2 indicates that only a small amount of the ultrasound energy will be reflected at a well bonded interface, and a large difference between Z_1 and Z_2 will have almost all the energy of the incidence wave reflected back to the probe, indicating very poor interfacial bond between tile and cement.[3] Poor interfacial bond could be due, to defects such is voids, delaminations, and air porosities between tile–cement interface. Such a strong reflection occurs even if the gap of the defect is as thin as 1μm. Hence, by scanning the tile surface and looking for a change in the reflected wave, one can, detect any bonding defect between the tile–cement. In this investigation, we are concerned with reflection of ultrasound from the tile–cement interface, i.e. the reflection coefficient, R. All other parameters are therefore kept constant, i.e. same batch of tiles, couplant, etc. In this situation, we can approximate R as

$$R = \frac{I_{\text{tile}}}{I_{\text{t-c}}} \tag{4}$$

where I_{tile} and $I_{\text{t-c}}$ are intensities of the reflected signal from the free, i.e. unbonded, tile back and tile–cement interface, respectively.

Defects that cause poor bonding have been investigated using the above criteria.[3]

EXPERIMENTAL PROCEDURE

The cement used was ordinary Portland cement mixed with water. This Portland cement was used to bond the tiles to a concrete slab of dimension 500 mm × 500 mm × 80 mm. Together they formed a layered structure as sketched in Fig. 1. The concrete slab surface was thoroughly cleaned with a damp sponge. This was to ensure that the slab was free from foreign particles that will weaken the adhesion strength. The tiles, having a thickness of 8mm, were semi-glaze homogeneous cut to dimensions of 25 mm × 25 mm. Different water–cement ratios of 0·3, 0·4, 0·5, 0·6, 0·8, 1·5 and 2·0 by weight were mixed by hand and spread on to the top surface of the slab to form a layer of 3–4mm thick mortar bed. The tiles were then placed onto the mortar bed and light tapping was applied around the tile to ensure that it was uniformly secured onto the mortar bed. Cubes of the same batch of water–cement ratio mixture were also made using detachable molds of dimensions 50 mm × 50 mm × 50 mm.

The tiled specimens were cured under natural environmental conditions. The cement cubes were taken out of their mold after 5 days when it was judged that the cubes were sufficiently hard not to fall apart on demolding. Assessments of the bonding strength of the tiles on the slab were carried out using a commercial flaw detector (Krautkramer USD10) which was operated in pulse–echo mode and connected to a computer for data transfer and further analyses. The hydration of the cement to the bonded tiles was evaluated by measuring the reflected signal amplitude.

The transmitter–receiver used was a normal (0°) 10mm, diameter 4MHz broadband compression probe. A thin viscous coupling gel was used to couple the probe to the surface of the tile. On the monitoring screen of the flaw detector, the amplitude of the reflected signal from the tile–cement interface was recorded as a percentage of the full screen height. The attenuator (signal amplifier) was kept constant. The waveform on the display screen was rectified which means that the phase change of any reflected signal could not be seen.

In monitoring the hydration of the cement cube, through transmission technique was used. This uses two separate probes as transmitter and receiver. In addition to measuring the transmitted signal amplitude in dB, the transmit time of the ultrasonic pulse through the thickness of the cube was also measured. The velocity through the cement was calculated. Two normal broadband compression probes of diameter 0·25 in and centre frequency 5 MHz, and two normal broadband shear probes of diameter 0·5 in and centre frequency 2·5 MHz were used to measure the compression and shear velocities, respectively, through the cement. The densities of the cement cubes were calculated using mass and dimensional measurements. The elastic modulus can be calculated from the two mode of velocities and the density.[4]

After the non-destructive evaluation, aluminum blocks of thickness 25·4 mm were bonded to the tile surfaces by an epoxide cement. The thickness of the blocks was designed to ensure that the pull-off force, from the top center of the aluminum block, could be transferred to and distributed evenly over the tile surface. The tiles were pulled off, perpendicularly to their surfaces, by a standard pull-off tester. A small section of the back surface of the tiles was examined using a scanning electron microscope (SEM).

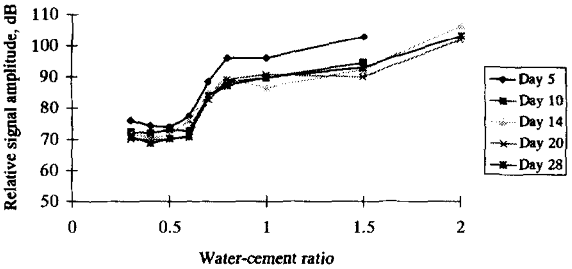

Fig. 2. Attenuation of signal amplitude with different water–cement ratio, used as adhesive in bonding tile to concrete slab.

RESULTS AND DISCUSSION

Hydration of cement

Figure 2 shows the relative signal amplitude for various water–cement ratios at different days of hydration. Each sample thickness was 50 mm. Therefore, from Fig. 2, samples having a water–cement ratio of 0·3 to 0·6 show an average attenuation of 1·5dB/mm on day 5 to 1·4dB/mm on day 28. Samples with a water–cement ratio above 0·7 show an average attenuation of 1·92dB/mm on day 5 to 1·83dB/mm on day 28. In all cases, the attenuation rate decreases exponentially as shown in Fig. 3 as the hydration rate progresses. For the same type of cement used, attenuation in the cement block is mainly due to scattering of elastic waves by air pores in the cement. Therefore samples with a high water content would have a bigger and higher distribution of air pores as water is either evaporated off or taken up in the hydra-

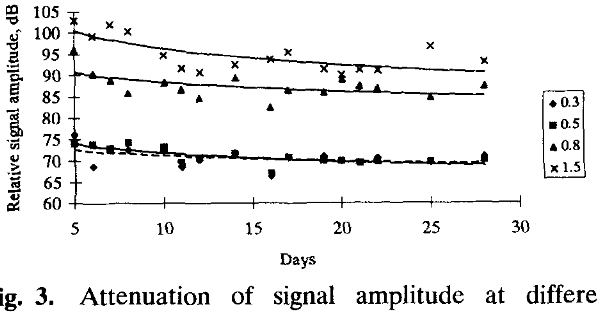

Fig. 3. Attenuation of signal amplitude at different hydration time in days, with different water–cement ratio as shown in the legend.

Table 1. Bulk density at day 28 for various water-cement composition

Water–cement ratio	*Density (kg/m³)*
0·3	1956
0·4	1921
0·5	1665
0·6	1351
0·7	1320
0·8	1140
1·0	938
1·5	785
2·0	720

tion process. This is quite evident as the bulk density of hydrated cement on day 28 for a water–cement ratio of 0·3 was found to be about 3 times heavier than hydrated cement for a water–cement ratio of 2·0. The bulk density for the various cements at day 28 is shown in Table 1.

Figures 4 and 5 show the compression velocity and shear velocity, respectively for various water–cement ratios at different days of hydration. A water–cement ratio of 0·3 gives the highest compression and shear velocities while a ratio of 2·0 gives the lowest velocities. The changes in velocities with hydration rate could not be reliably seen within the experimental error of our measurement that is estimated to be about 5%. Nevertheless, there is a positive increase in velocities as the hydration progresses from a soft paste state of low acoustic impedance on day 5 to a hard brittle solid of high acoustic impedance on day 25. Dimensional and density changes could not be reliably monitored with the size of our samples and equipment used. Figure 6 is a plot of the elastic modulus on day 28. The modulus decreases as $Cx^{-1\cdot8443}$, where $C = 0\cdot5$ GPa and x = water–cement ratio. The coefficient of fit was 0·9983.

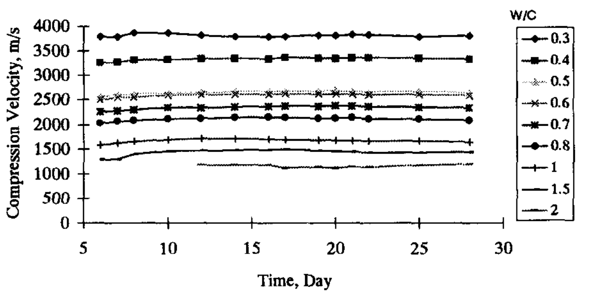

Fig. 4. Compression velocity at different hydration time in days, with different water–cement ratio as shown in the legend.

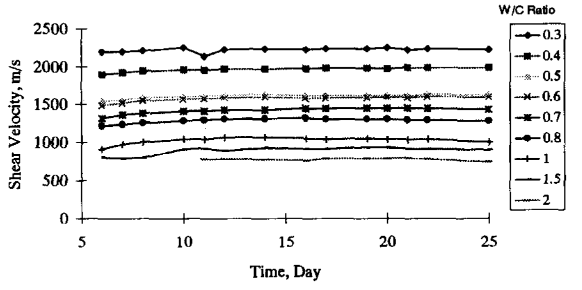

Fig. 5. Shear velocity at different hydration time in days, with different water–cement ratio as shown in the legend.

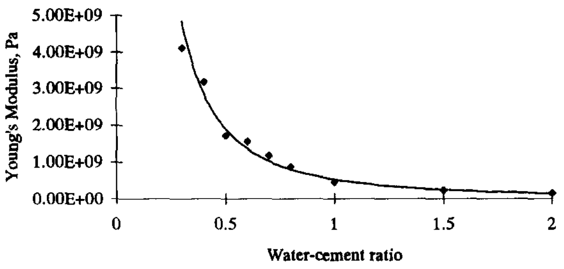

Fig. 6. Young's modulus of hydrated cement at day 28 with different water–cement ratio.

Tile–cement bond

A poor bond (water–cement ratio of 0·8) and a good bond (water–cement ratio of 0·5) between cement and tile is shown in Figs 7(a). and (b), respectively. The figures are from the display of the flaw detector. The signal amplitude is higher (poor impedance coupling) for a bad bond than for a good bond.

Figure 8(a) shows the mean relative amplitude of the reflected ultrasonic signal from the cement–tile interface with various water–cement ratios at different days. The signal is referenced to the reflection from the back of the tile without any load, i.e. unbonded. Therefore in accordance with eqn (4), this would give a reflection coefficient of 1 or 100% reflected signal amplitude. From Fig. 8(a), the minimum relative amplitude occurs at water–cement of 0·5 to 0·6 showing that at this water–cement ratio, good bonding condition is achieved for this particular tile and cement. Worst bonding occurs for a water–cement ratio of less than 0·3 and greater than 0·7. This is similar to Fig. 2 where the signal amplitude is a minimum for water–cement ratio of around 0·5. This shows

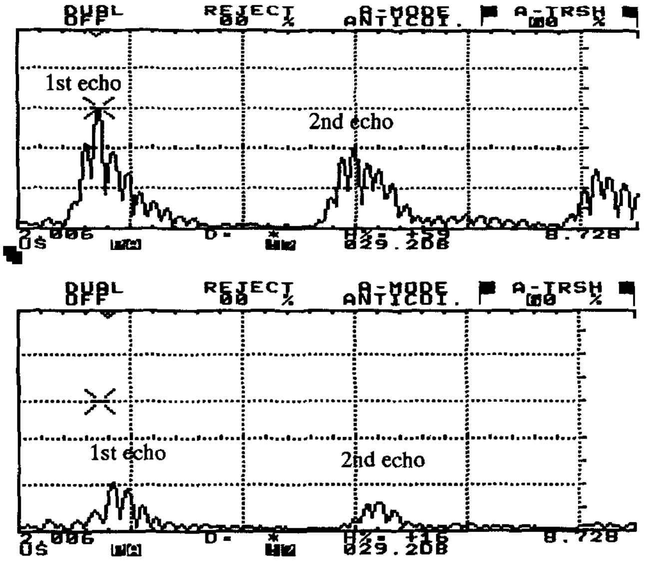

Fig. 7. (a) An example of a reflected signal amplitude for a poor bond (cement with water–cement ratio of 0·8). The gated first echo has H% = 59. A free tile has H% = 100, i.e. full screen height and (b) an example of a reflected signal amplitude for a good bond (cement with water–cement ratio of 0·5). The gated first echo has H% = 16. A free tile has H% = 100, i.e. full screen height.

that a water–cement ratio of around 0·5 gives the best acoustic impedance matching between these particular two media.

Figure 8(b) shows the mean relative amplitude of the reflected ultrasonic signal, from the cement–tile interface, at different days, during the hydration process of the cement for water–cement ratio of 0·3, 0·5, 0·6 and 0·8. From Fig. 8(b), there is a slight increase in the percentage reflected signal amplitude as water is taken up in the hydration process of the cement leaving air pores (Fig. 10(a) and (b)). The gradient of the curves would approach a constant value as the hydration is completing.

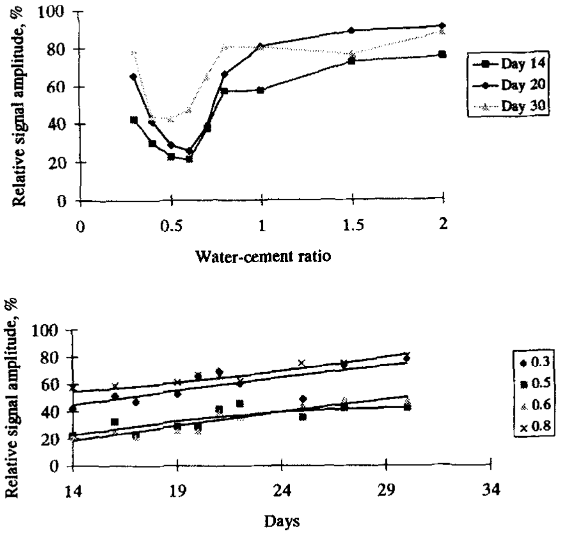

Fig. 8. (a)Relative signal amplitude of cement–tile interface with different water–cement ratio and (b) relative signal amplitude in monitoring the setting of cement–tile interface with different water–cement ratio as indicated in the legend.

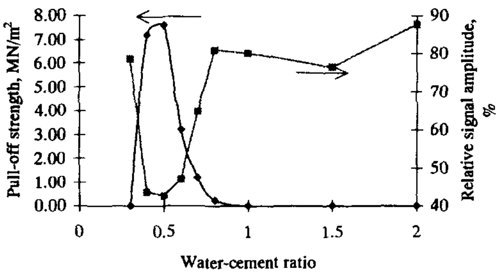

Fig. 9. Pull-off strength of cement–tile interface and ultrasonic measurement of relative signal amplitude on day 30 for various water–cement ratio.

Pull-off test

Figure 9 shows the pull-off strength of the cement–tile interface with various water–cement ratios. Unfortunately, the pull-off tester's scale has an interval of only 0·1KN, thus points at the zero abscissa indicate a pull-off strength of less than 40KN/m^2. It can be seen that the pull-off strength correlates with the mean reflected ultrasonic signal amplitude of Fig. 8(a). The difference between the maximum and minimum signal amplitudes is 1·9 times or 5·6dB. The corresponding difference in pull-off strength is 1·9MN/m^2. The pull-off strength does not correlate with the elastic modulus of the hydrated cement with different water–cement ratio (see Fig. 6).

Figures 10(a) and (b) show crystals of hydrated cement adhering to the tile back. These crystals grow into the pores of the tile back, thus bonding the tiles to the cement. The pores thus act as anchoring points for the hydrated cement crystals. The disbond between tile and cement is due to crystal fibre breakage and fibre-pull out from these anchoring points. For a water–cement ratio of less than 0·3, hydration of cement is only partial, giving a weak bond while a ratio of greater than 0·8 does not have enough cement to bond the tile leaving a very porous cement–tile interface.

Although, cement with water–cement ratio of 0·3 has the highest dynamic Young's modulus of elasticity, the bonding strength of the cement to the tile, as measured by ultrasonic means and the pull-off test, does not give a very good bond in comparison to a cement with a water–cement ratio of 0·5. Here the cement block is considered as one homogeneous and/or monolithic block or as a single layer medium whereas, the tile–cement interface, where the bonding quality is evaluated, is a two layered media. Therefore, in practical terms, evaluation of strength of cement alone will not correlate to the cement strength of cement to tile. The entire layered media have to be evaluated to determine the bonding strength of cement to tile.

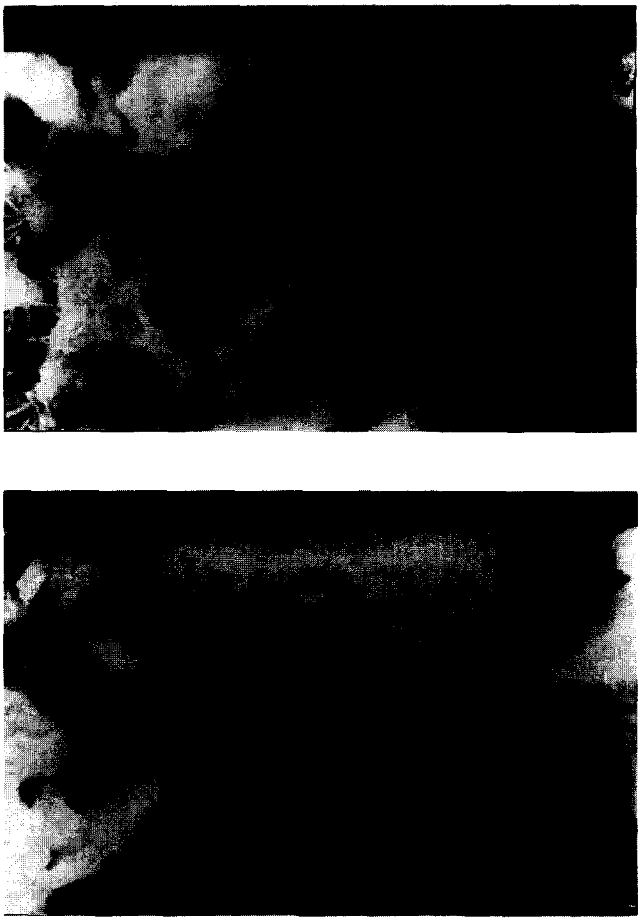

Fig. 10. (a)SEM picture of crystals of hydrated cement on tile surface (water–cement ratio 0·5) and (b) SEM picture of crystals of hydrated cement on tile surface (water–cement ratio 2).

CONCLUSION

The reflected signal amplitude of the pulse-echo ultrasonic technique has the capability of evaluating the bonding strength of cement to tile. This can be related to the critical pull-off strength that is very much the key factor dictating the performance of the tiled wall system under external mechanical and weathering loads. Evaluating the mechanical strength of the cement alone does not correlate with the bonding strength of the same cement to tiles but rather the tile–cement interface has to be evaluated as a layered system. SEM examination shows that the pores in the tile provide the anchoring points for the hydrated cement crystal to bond the tile to the cement. To the authors' knowledge, there are no non-destructive techniques employed in evaluating bonding strength of tiles in buildings. This ultrasonic technique might have the potential for this purpose. It also has the capability of detecting and measuring voids in tiled wall that also contribute to bonding failure. Further research is under way to evaluate this technique for field application and criteria for bonding failure.

ACKNOWLEDGEMENTS

K.S. Tan would like to thank the University of Brunei Darussalam, Brunei Darussalam for supporting his research at Nanyang Technological University, Singapore.

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