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DIAGNOSING IN SITU CONCRETE BY NON-DESTRUCTIVE TEST METHODS

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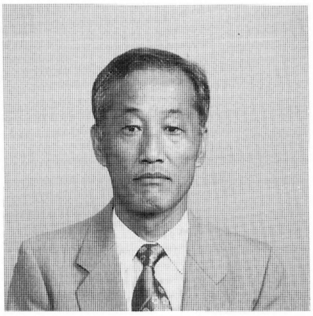
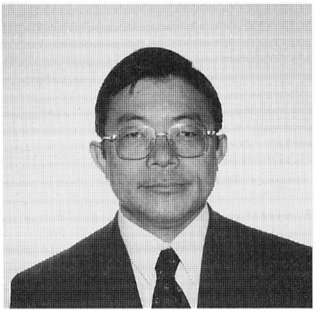
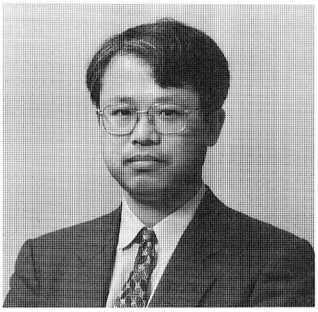

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ABSTRACT

In general, small specimens have been used in the non-destructive testing of concrete. However, there may be significant differences in the quality of the concrete used for such specimens and in situ concrete because of the differences in the methods of compacting, curing of concrete and moulds, etc. In this paper, non-destructive testing techniques, such as measuring the velocity of ultrasonic pulses through the concrete, infrared thermography, and gamma radiography were used to detect regions of defects of in situ concrete up to the age of 2 months, beginning immediately after compacting the concrete. The specimens used in this investigation were four reinforced concrete beams with a nominal height of 1200 mm, a web width of 500 mm, and a length of 1200 mm to simulate a full-size beam. The effects of defects were simulated by casting three types of concrete: well compacted concrete with artificially induced defects; uncompacted concrete; and poorly compacted concrete.

Keywords: Non-destructive test, in-situ concrete, internal defects, ultrasonic pulse velocity, infrared thermography, gamma radiography

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1. INTRODUCTION

Material deterioration, such as corrosion of the reinforcement and alkali-aggregate reactions, is often induced and accelerated by such initial defects as poor compaction, segregation, and initial cracks. Techniques for non-destructive testing (NDT) of concrete, which confirms whether well compacted concrete has reached every part in the mould or not, have not yet to be established.

In the study on NDT of concrete, small specimens made with homogeneous concrete have been used. On the other hand, it is well established that the properties of in-situ concrete will vary within a member, due to differences of compaction and curing as well as non-uniform supply of material, but typical relative strength variations according to member type are also widely known[1]. These variations, however, can only be regarded as indicating general trends which may be expected, since individual construction circumstances, such as the mix proportion, the consistency of the fresh concrete, the degree of compaction, and the workmanship, may vary widely.

NDT techniques, such as measurements of UPV (ultrasonic pulse velocity) through the concrete, infrared thermography and radiography, can be used to detect defective or deteriorating regions. However, it is not obvious how to confirm that a member have been cast with well compacted concrete by these techniques after casting. Because of this is important to investigate the variations in the quality of the concrete and to study how to confirm whether a member has been cast with well compacted concrete or not. This paper gives results of an investigation into the use of NDT on defective reinforced concrete beams.

The main objectives of this investigation were to study distributions of and variations with time in UPV of reinforced concrete specimens with a full-size cross section, and also to study the advantages and limitations of UPV measurements, infrared thermography, and gamma radiography by casting two specimens (one with no compaction, one with poorly compacted concrete) in addition to a specimen with well compacted concrete.

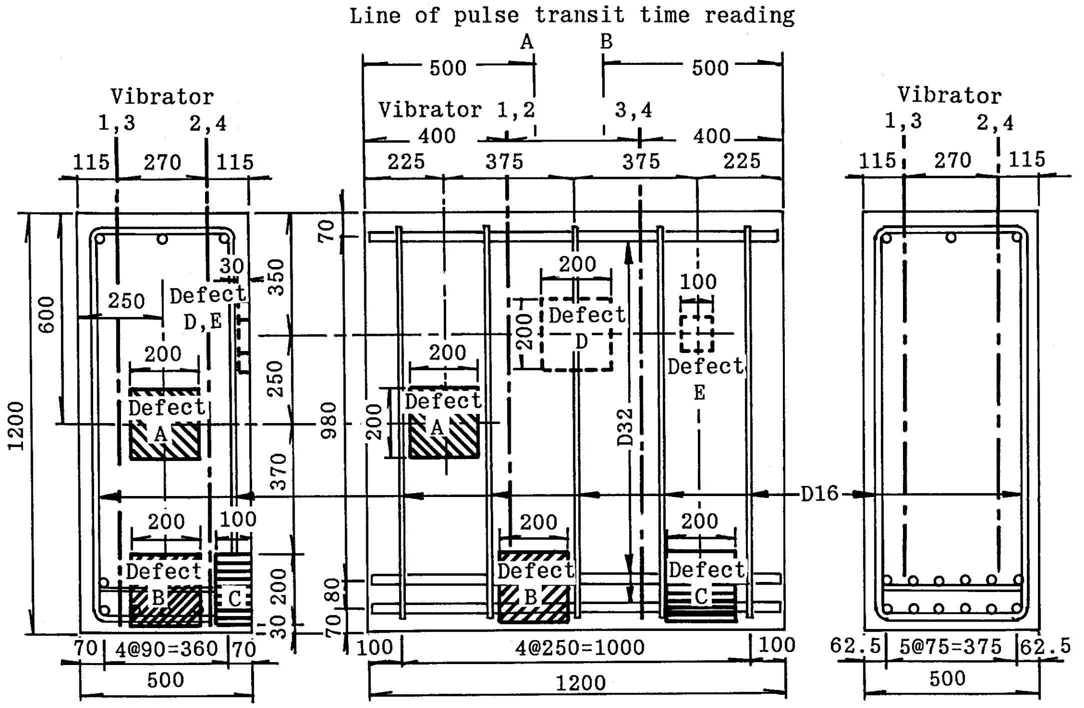
2. TEST PROGRAMME

2.1 Specimens

The specimens used in this investigation were four reinforced concrete beams with a nominal height of 1200 mm, a web width of 500 mm and a length of 1200 mm. The effects of defects were simulated by casting with three conditions: well compacted concrete (beam 1) with vibrating periods of 15 seconds with artificially induced defects; poorly compacted concrete (beams 2 and 4) with vibrating periods of 2 seconds[2]; and no compaction (beam 3).

Details of the specimens are shown in **figure 1**. Two re-bar arrangements were used: a standard reinforcement (8-D32, beams 1 and 2); and an over-reinforcement (12-D32, beams 3 and 4). Plywood and permeable panels were used for the concrete form. Except for beam 3, which was cast with no compaction, each beam was cast in two lifts without construction joints with a poker vibrator (12,000 rpm, 400 watts) fixed at four positions, as shown in **figure 1**. The artificially defects of beam 1 were defects with only coarse aggregate (defects A, B and C) to simulate honeycombing, and with 30-mm-thick expanded polystyrene plates (defects D and E) fixed on the mould to simulate a void. The types of specimen are shown in **table 1**.

Beams were cured within moulds covered with a polythene sheet for the first



(1) Standard re-bar Arrange. (Side view) (2) Over re-bar Arrange.

Fig.1 Specimen Details and Location of Defects

three days after casting. The specimens of beam 1, in the form of 100-mm-diameter cylinders, were cured in water at 20±2°C immediately after demoulding at the age of 24 hours. After demoulding, beams were kept outdoors.

Table 1 Types of Specimen

No. of specimen	Re-bar arrangement	Concrete form	Vibrating period(s)
1	Standard	Plywood	15
2	Standard	Permeable	2
3	Over	Plywood	No compaction
4	Over	Plywood	2

2.2 Concrete mix and materials

Ready mixed concrete with a nominal strength of 210 kgf/cm^2 were used. The mix consisted of 1:2.9:3.9 (cement:sand:coarse aggregate) by weight, having a cement content of 277 kg/m^3 and a water-cement ratio of 0.57. An air-entrained concrete was used with a slump of 80±10 mm and an air content of 5±1%. The fine aggregate was a pit sand, and the coarse aggregate consisted of a pit gravel and crushed stone with a 25 mm maximum size. The cement used was ordinary Portland cement.

The concrete was poured under a hot sun at an air temperature of about 30°C. The results of tests on fresh concrete are shown in table 2. The slump and the air content satisfied the specified conditions in this study. The compressive strength of the concrete at the age of 28 days obtained from accompanying specimens of beam 1 was 27.8 N/mm^2, the unit weight was 2.28 t/m^3 and Young's modulus was 27.0 kN/mm^2.

Table 2 Properties of fresh Concrete

Specimen	Beam 1	Beam 2		Beam 3	Beam 4	
		1st lift	2nd lift		1st lift	2nd lift
Slump (mm)	90	75	80	75	80	80
Air content (%)	5.1	4.1	4.6	5.1	5.0	4.5

2.3 Measurements

Infrared photographs were taken with an infra-red camera with the long wavelength of 8 to 13 micrometres at hourly intervals under the following conditions:

1) From immediately after compacting until midnight
2) From the age of 24 hours to immediately before demoulding
3) From immediately after demoulding to about 24 hours.

On taking infrared photographs, the surface of the specimen was kept in the shade with a vinyl sheet to eliminate the influence of the rays of sun.

Pulse transit times were measured with a PUNDIT incorporating lead zirconate titanate ceramic transducers of frequency 54 kHz with a 1000-volt energising pulse and 2-microsecond duration, and with an input sensitivity of 250 microvolts. The softest grease possible was used as the couplant to ensure good acoustical contact with the transducers pressed against the concrete surface. The transit time was read repeatedly until a minimum value was obtained in order for the layer of couplant to spread thinly.

The pulse transit time was sampled under the following conditions:

1) Up to 5 hours from immediately after compacting
2) the day before demoulding at the age of 3 days
3) at the ages of 4 and 28 days.

Pulse transit times were measured at the center of the specimen on the conditions 1 and 2, and at a regular grid of the intervals of 100 mm or 200 mm over the specimens on the condition of 3. Pulse transit times of zones with defects and of the re-bar arrangement were measured at a regular grid of the intervals of 50 mm.

Radiography method was taken at the age of 8 weeks after moving specimens from the site, because of the need for extensive safety precautions. In this method, a 370-gigabecqurel cobalt 60 source and an imaging plate as the photosensitizer were used. The imaging plate was held against the back face and sandwiched between thin lead screens, which intensity the photographic image produced on the imaging plate. The exposure dose of cobalt 60 was 92.5-gigabecqurel-hr. The radiographic data recorded on the imaging plate were read by a He-Ne laser beam scanning, and was exposed on the film after visualizing by means of computer graphics.

3. RESULTS AND DISCUSSIONS

3.1 Assessment of defects by infrared photography

The surface temperature of the plywood panel of all specimens immediately after compacting the concrete was between 29 and 34^{o}C, and there was a tendency for the temperature of the panels to drop towards the bottom of the specimen. However, it was impossible to detect expanded polystyrene plates of defect D and E in contact with the inside of a panel of beam A. At 17:00 after about 5 hours of compacting, the temperature of the panel with these defects had dropped about 1^{o}C than around the defect, but the shape of the defect was not clear. At 22:30 after 13 hours of compacting, the surface temperature of these zones falls 2 to

$4^{o}C$ than around defects, and the shape of the defects is very clear, as shown in **figure 2**.

At 14:30 on the day after pouring, the temperature difference between zones with defects and around defects is only $0.5^{o}C$, and it is practically impossible to find defect E of 100 x 100 mm, as shown in **figure 3**. The surface temperature with these defects drops than around defects, as the atmospheric temperature falls after sunset, and then these zones is a low temperature of about $2^{o}C$ than around defects, as shown in **figure 4**. On the other hand, it was impossible to find the defect C made near the surface of the specimen by coarse aggregate.

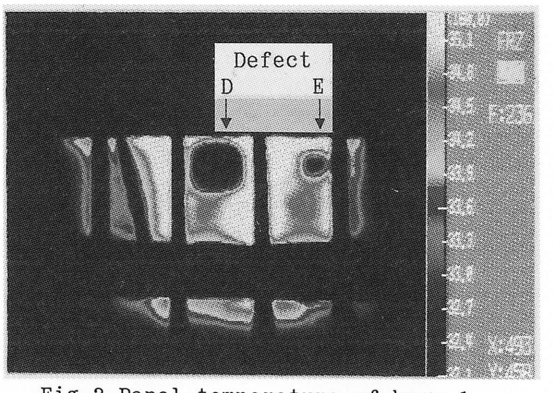


Fig.2 Panel temperature of beam 1 after 13 hours of pouring

Needless to say, there was much honeycombing and many zones of no concrete around stirrups at the surface

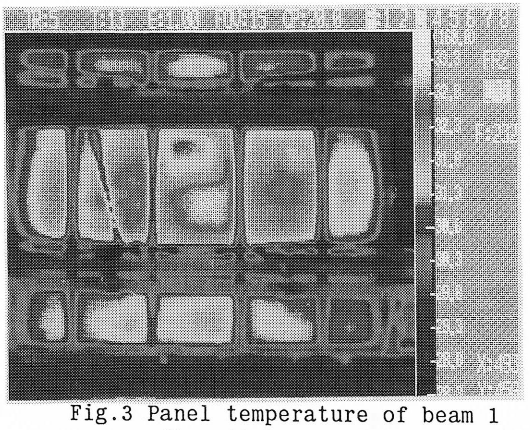


Fig.3 Panel temperature of beam 1 after 28 hours of pouring

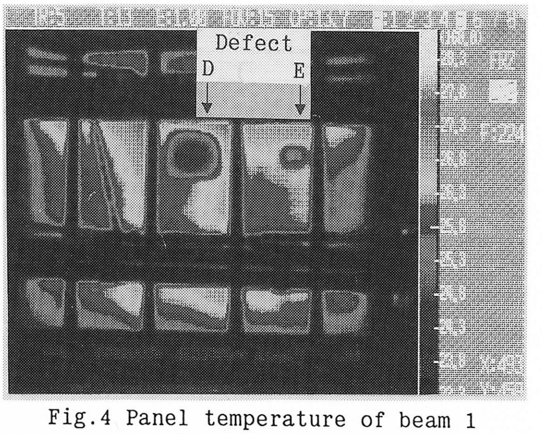


Fig.4 Panel temperature of beam 1 at the age of 2 days

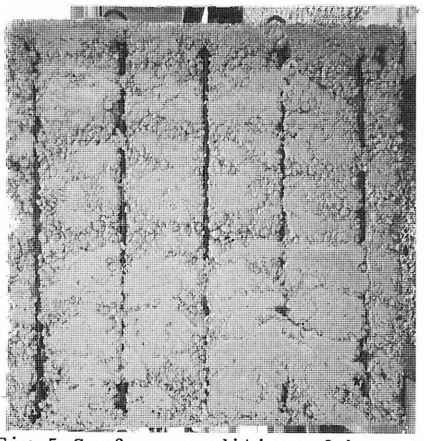


Fig.5 Surface condition of beam 3

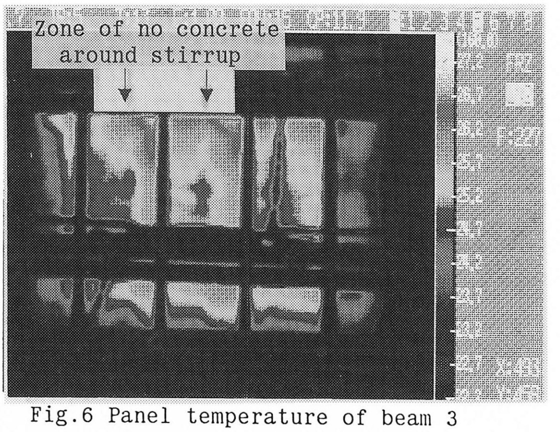


Fig.6 Panel temperature of beam 3 with no compaction

of a specimen cast with no compaction, as shown in **figure 5**. The panel surface with the zone of no concrete around the stirrup was a low temperature of 0.5°C than around these zones at 18:00 after about 9 hours from compacting. At 14:00 on the day after casting, there was no temperature difference between the zones of no concrete around a stirrup and its surroundings, and then these zones was again a low temperature of 0.5 to 1°C than its surroundings at 22:00, as shown in **figure 6**. Therefore, it is possible to find the zones of no concrete around the stirrup from the distribution of the surface temperature of the panel, because there is a good agreement between areas of the low temperature and the position with the zones of no concrete.

3.2 ASSESSMENT OF QUALITY AND DEFECTS OF CONCRETE BY UPV

Figure 7 shows plots of UPV observations on the panel at the center of beam 1. The UPVs can be observed after about 3 hours of compacting of concrete, and its UPV is about 0.3 km/s. In general, the UPV of the fresh concrete with the path length of 100 mm is 0.1 to 0.3 km/s immediately after compacting, and is about 0.5 km/s after 3 hours of compacting[3]. The UPVs of the fresh concrete in this study is very small because of the long path length and the large attenuation of the pulse. In addition, it was impossible to measure the pulse transit time at the position of defect D until the concrete hardens. From these results, it is possible to find a large void in concrete when observing UPVs after a few hours of pouring. However, it was impossible to measure the pulse

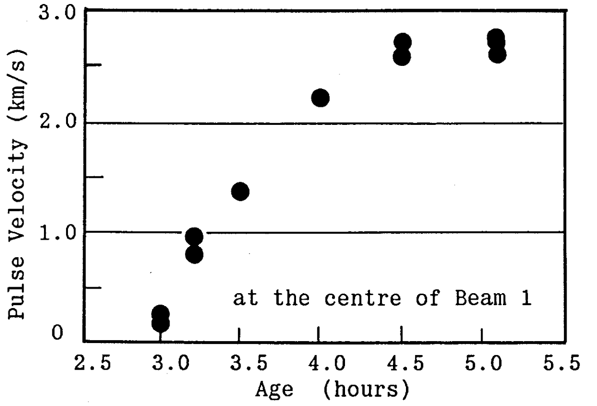


Fig.7 Pulse velocity of fresh concrete

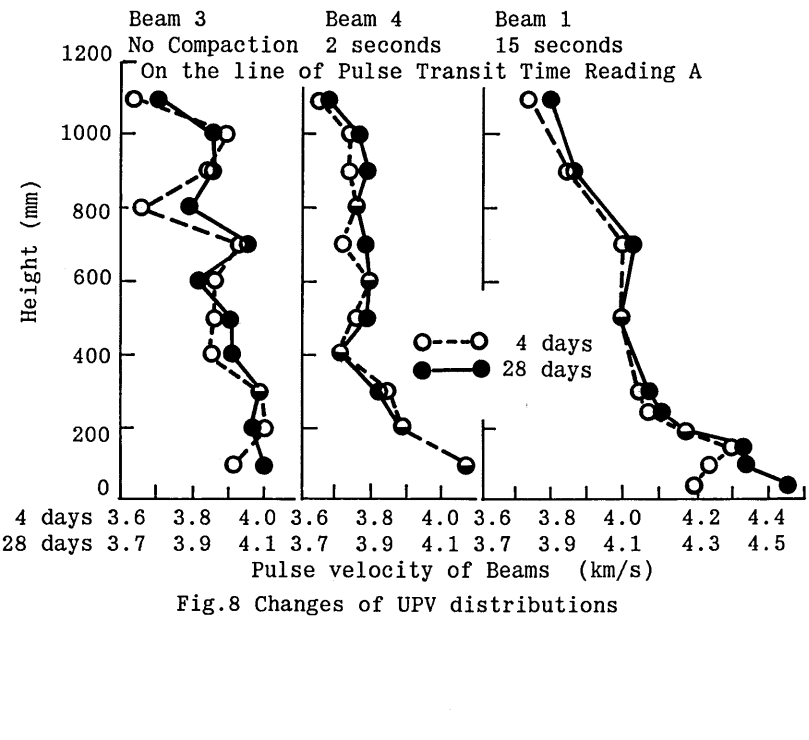


Fig.8 Changes of UPV distributions

transit time after hardening, because there is no bond between the concrete and the mould.

Figure 8 shows plots of UPV observations at the ages of 4 and 28 days at each level for three specimens made by plywood panels: beam 1 with well compacted concrete; beam 3 with uncompacted concrete; and beam 4 with poorly compacted concrete. For these specimens, UPV increases from the age of 4 to 28 days, but there is little change in distribution from 4 to 28 days. For neither specimen, with very different degrees of compaction, does the UPV distribution down the specimen change with time. The UPV gradients of the specimen with well compacted concrete is reasonably uniform and may agree with the strength gradients[1]. The UPV gradients of beam 2 is smaller than beam 1. On the other hand, UPVs of beam 3 with no compaction increase towards the bottom. This means that at the lower level of beams, the concrete is compacted due to its own weight effects. Thus the general tendency will be for strengths to be highest near the base of pours and lowest in the upper regions. The UPVs in the bottom 200 mm of beam 1 and 4 are too large, because the UPVs in this regions may be affected by main reinforcement[4].

Although beam 1 was cast with well compacted concrete, there are some zones in the middle of the beam with lower UPVs than the upper or lower zones, as shown in **figure 8**. It is obvious that the strength of these low UPV zones is less than that of the high UPV zones, and they may consist of insufficiently compacted concrete[5].

Generally, high UPV readings in concrete indicate concrete of good quality, and Leslie and Cheesman have reported that concrete with UPV readings over 4.58 km/s is excellent quality, and also that concrete with UPV readings between 3.66 and 4.58 km/s is good quality [6]. The UPV readings of specimens in this study were over 3.6 km/s at the age of 4 days, even for a beam 3 cast with no compaction. Needless to say, there was much honeycombing and many zones where concrete was absent around the stirrup at the surface of beam 3 cast with no compaction, as shown in **figure 5**. This concrete quality is very poor for the durability of concrete structures, but it may be judged that this concrete quality is good based on the UPV value alone.

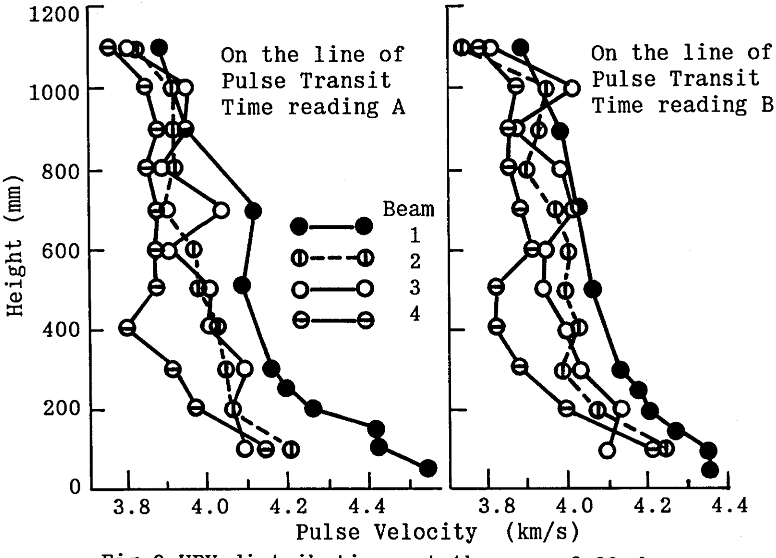


Fig.9 UPV distributions at the age of 28 days

Figure 9 shows plots of UPV observations at each level near the positions of the vibrators. Although specimens were cast with almost identical properties, as shown in **table 2**, there is a significant difference in UPVs and their distribution for each beam according to the position of the pulse. These results mean that concrete is inherently heterogeneous, and that it may be too difficult to cast in situ concrete with a uniform UPV. Therefore, from the above results, it can be inferred that to assess the quality of the concrete in existing structures by measuring the UPV through the concrete, it is necessary to obtain not only UPV values but also UPV distributions.

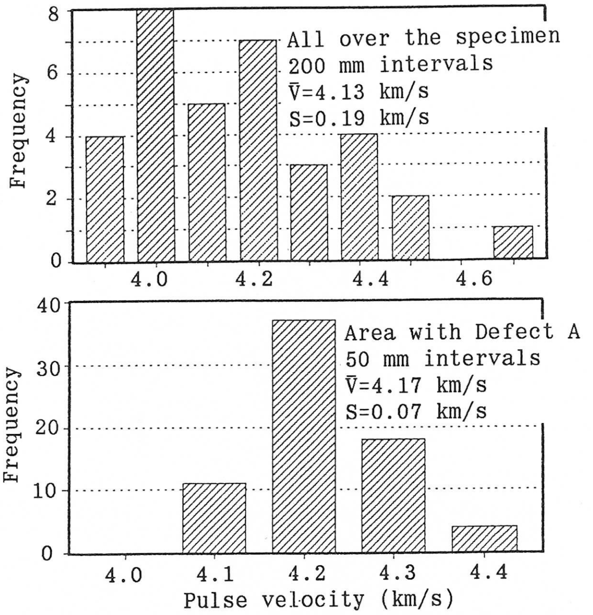


Fig.10 Frequency distribution of Beam 1

The UPVs of beam 1, measured at the grid of 200 mm at the age of 28 days, is not a normal distribution, and the mean value ($\bar{V}$ =4.13 km/s) is less than the mean UPV (4.17 km/s) of the zone with the defect A that was measured at the grid of 50 mm, as shown in **Figure 10**. On the other hand, the UPVs of the zone with defect A show a normal distribution, and is within $\bar{V}\pm S$, where S is the standard deviation. And also, UPVs of the zone with defects B and C shows a similar tendency. This is because these defects were made from coarse aggregate with a UPV larger than the mortar[7]. Furthermore, UPVs more than $\bar{V}\pm S$ are in the zones with insufficiently compacted concrete or in the areas where the UPV may be affected by the reinforcing bar. Therefore, it may be difficult to detect honeycombing by only UPV or $\bar{V}\pm 2S$, as proposed by Chung[8] and reported by Tomsett [9].

3.3 Assessment of defects by radiography

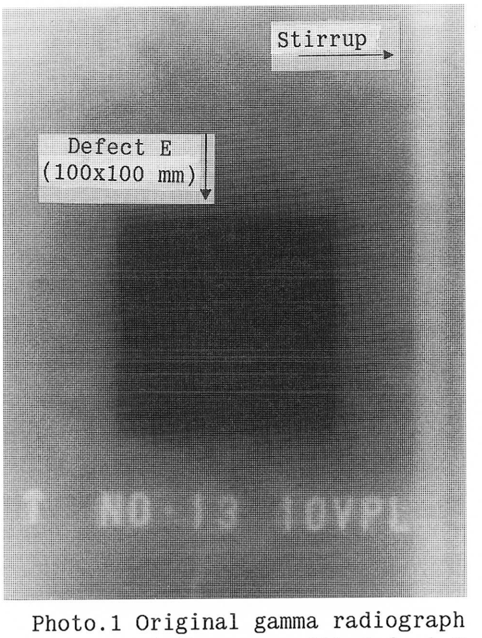


Photo.1 Original gamma radiograph of the zone with defect E

Photograph 1 is an unenhanced gamma radiograph of the zone with defect E of beam 1. It is easy to recognize the stirrup and defect E with the thickness of 30 mm. However, it was difficult to recognize defect C made from the coarse aggregate by the original radiograph, and then, the light intensity of this original radiograph was increased by computer enhancement. As a result, defect C can be recognized to be a pattern as honeycombing at the position of the reinforcing bar, although the shadow of the stirrup becomes unclear, as shown in **photograph 2**.

The zone with lower UPV in the middle of the beam 2 as compared with the UPV of the upper or the lower zones may consist of poorly compacted concrete, and then the radiograph of this zone was also enhanced by computer as same as the **photograph 2**. It can be recognized this zone as to be a very few shadow, as shown in **photograph 3**. From this results, it maybe recognize the zone with poorly compacted concrete by the gamma radiograph that its light intensity was increased by means of computer enhancement.

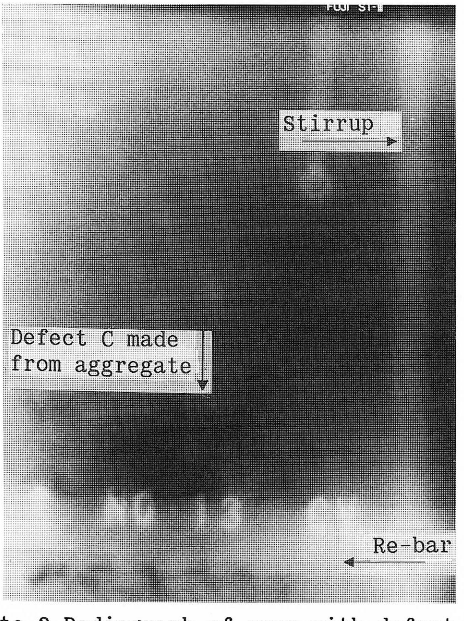


Photo.2 Radiograph of zone with defect C after increasing the light intensity

Photo.3 Radio graph of zone with not well compacted concrete

4. CONCLUSIONS

(1) It may be possible to find a void near the surface of the concrete and zones with no concrete around the stirrup by infrared photography of plywood panels after the hardening of concrete, although it is impossible to find before hardening.

(2) Immediately after compacting, it is impossible to measure UPV through the concrete with the full scale size, but there may be voids in the portion where it is impossible to measure UPV at the time to be able to measure UPV.

(3) UPVs of beams increase towards the bottom, and there is little change in UPV distribution with time. In such a beam with a insufficient compaction, however, there is a large variation in the UPV in the direction of the height, and there is a small difference in UPV between the top and the bottom of the beam.

(4) Even in beams cast with well compacted concrete, there are differences in UPVs and its distributions between beams, and according to the direction of the pulse. It can be inferred that to judge the concrete quality of existing structures by measurements of UPV through the concrete, it is necessary to obtain not only UPV values but also UPV distributions.

(5) It is easy to recognize a change in thickness of 30 mm by the original gamma radiograph, but it is necessary for the light intensity of radiograph to be increased in order to recognize honeycombing and zones with poor compaction.

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