Determination residual strength concrete of post-fire using ultrasonic pulse velocity

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Abstract. Assessment of residual strength of concrete post fire is importance. Concrete exposed at high temperatures causes chemical and physical phenomena that cause various level of damage. Heat distribution unevenly causes different of hot spots on the concrete surface. The correlation between high temperature and duration heat raises the heat penetration depth differently which effect on the strength of concrete. The research aims determine substantial reduction of the compressive strength concrete the post-fire as result of the depth of heat penetration. Experimental method by vertical furnaces was used in this research. Specimens use two of the concrete panel which has 1065 mm x 1055 mm and 100 mm thickness and ten the cylinder concrete with the diameter 150 mm and 300 mm height. Combustion of the specimens was performed with gradual heat follow the heat curve according to SNI 1741: 2008. The combustion duration carried out for 2 hours and an hour that result the depth heat penetration differently. The depth heat penetration was measured with a set thermocouple that has embedded in the concrete panels with various depths. The residual concrete strength post-fire was measured using ultrasonic pulse velocity.

1. Introduction
Concrete is a material widely used material in building industry. As an incombustible material are often used for structural fire protection [1]. Although concrete is inflammable, when concrete exposed to high temperature, there is degradation on its properties [2].

The assessment of deteriorated concrete structures after fire is needed in order to identify the level of damage induced by the chemical and physical possess taking place [3]. The residual structural capacity has to be accurately addressed when the safety of the structure is in risk, in order to define the best strategy for repairing or to decide on its demolition. The residual structural strength is influenced by several factors such as the heat intensity, the pattern of fire exposure and the quality of building materials.

The nondestructive techniques are used for assessment the level of damage of concrete structure. One of most NDT method used to assess internal characteristics is ultrasonic pulse velocity (UPV). A several studies to examine the change of in pulse velocity and strength of concrete subjected to elevated temperature were performed by many authors [1][4][5][6][7][8][9]. Experimental studies on the use of UPV have been carried out to investigate how pulse velocity was affected by the damage of concrete.
cause by time exposure of fire. There were several previous studies [10] reserach the relationship between
the residual strength concrete to dimension of side exposure to fire differently.
This paper discusses the assessment of damage concrete in post-fire which caused by the exposure
duration of fire. The purposed of the study was to evaluate the residual strength and to identify the depth
of heat penetration.

2. Methodology

2.1. Ultrasonic pulse velocity evaluation of concrete
Nondestructive test (NDT) methods has seems to be the standards of many countries [11] and are used to
evaluate the condition of concrete in buildings [12]. There are two methods that are popular, surface
hardness and ultrasonic pulse velocity (UPV)[13].
The test instrument consists of pulse generator and transmitter and pulse receiver. Pulses of
longitudinal stress waves are generated by an electro-acoustical transducer that is held in contact with one
surface of the concrete under test [7][8][16]. The pulses are received and converted into electrical energy
by a second transducer located a distance \(L\) from the transmitting transducer. The transit time \(T\) is
measured electronically. The pulse velocity \(V\) is calculated by a equation (1). The principle is that the
speed of propagation of stress waves depends on the density and the elastic constant of the solid. In
concrete member, variation in density can arise from non-uniform consolidation and variation in elastic
properties can occur due to variations in materials, mix proportions, or curing [6, 9].

\[
V = \frac{L}{T}
\]  

Where:
\(V\) = pulse velocity, m/s
\(L\) = distance between centers of transducer faces, m,
\(T\) = transits time, s

By determining the stress waves speed at different location is possible to determine about the
uniformity of the concrete. The testing principle is illustrated in Figure 1 which describes the path of
ultrasonic pulses as the wave travel from one side of a concrete member to the other side.

![Figure 1. Effect of defects on travel time of ultrasonic pulse [12]](image-url)
The top case represents the shortest travel time through sound concrete. The second case from the top represents a path that passes through a portion of inferior concrete. The third case shows a diffracted path around the edge of a large void (or crack) and it would result in greater travel time than the first case. The last case indicates a travel path that is interrupted by a void. This air interface result in total reflection of the stress waves and there would be no arrival at the opposite side. A comparison of wave speeds at the different test points would indicate the areas of anomalies within the member [12].

Figure 2 illustrates the testing principle of comparison wave speed measurement that has also been used on the same surface. This approach determine the depth of a fire-damaged surface layer having a lower wave speed than the sound concrete layer [12]. The test is carried out by measuring the travel time as a function of the distance X between transmitter and receiver. The method assumes that stress-wave arrival at the receiver occurs along two paths. Path 1 is directly through the damage concrete, Path 2 which is through the damage and the sound concrete. For small separation, the travel time is shorter for Path 1, and for large separation, the travel time is shorter for Path 2. By plotting the travel time as a function of the distance X, the presence of a damage surface layer is indicated by a change in the slope of the data. The distance X0 at which the travel times for the two path are equal, is found from the intersection of the straight lines as shown in Figure 2(b). The slopes of the two lines are reciprocals of the wave speeds in the damage and sound concrete. The depth of the damaged layer is found from the equation (2).

\[ d = \frac{X_0}{2} \left( \frac{V_s - V_d}{V_s + V_d} \right)^{\frac{1}{2}} \]  

(2)

2.2. Laboratory testing

2.2.1 Materials

Material used for making specimens include cement (C), water, fine aggregate (FA) and coarse aggregate (CA). The cement used was Portland Composite Cement (PCC) Tiga Roda type I. Fine and coarse aggregate used were obtained from local availability.

2.2.2 Experimental specimens

The concrete was mixed according to volumetric proportions of C:FA:CA that has ratio 1:1.5:2.5. A water cement ratio (w/c) of 0.58 was considered to make experimental specimens with strength level in 28-days
approximately 19 MPa. The cement paste occupies 25% of the total concrete volume (V_{paste} = 25%). The volume ratio of fine aggregate to total aggregate (S/A: sand/aggregate) is 40%.

Table 1 show the concrete specimens used in this study. Two type shape specimen were used in this study, the concrete specimens were cast in steel cylinder molds and in timber square molds.

| Type          | Size          | Number specimens |
|---------------|---------------|------------------|
| Cylindrical   | 300 x 150     | 10               |
| Wall panel[18]| 1065 x 1055 x 100 | 2               |

After curing the concrete specimens were maintained at temperature room. In term to obtain the specimen in dried state, the specimens have been dried for minimum 2 month in well ventilation room [18].

\[ T = 345 \log_{10}(8t + 1) + 20 \]  

Where:
\[ T = \text{heating temperature, °C} \]
\[ t = \text{elapsed time, s} \]

![Figure 3. Heating rate in experiment[19]](image)

In this study, the concrete specimens were divided in 3 group based on time-elapsed heat (1) unheated, (2) An hour, and (3) two hour. The specimens were also divided based on side-exposure of fire, 1-side and 3-side. The classification and number of specimens are detailed in Table 2.

Five of the cylindrical specimens were heated on 4-side exposure and the wall specimens were heated on one side exposure at the vertical position. After the target temperature was reached the furnace was switched off. The specimen were removed immediately from the furnace and cooled at the temperature room for 7 days.
Table 2 Conditioning of specimens

| Time elapsed heated | Temp. Max (°C) | 1-side exposure | 3-side exposure |
|---------------------|----------------|-----------------|-----------------|
| 0                   | 0              | 2               | 5               |
| 1 h                 | 965.8          | 1               | 2               |
| 2 h                 | 1045.5         | 1               | 3               |

1-side exposure was represented by wall specimens
3-side exposure was represented by cylindrical specimens

This heating parameter can lead to various degree of damage to concrete specimens. The temperature inside the wall concrete specimens was measured by the embedded thermal couple (type K) of 0.65 mm in diameter. Hot junctions to measure the heating temperature shall are set as shown in Fig. 4, center and middle points between center and end part on the center line of test surface of wall specimens symmetrically. The number thermocouples for wall specimens with size type C was placed on 5 measuring points [19][18]. Each measuring points was embedded five the thermocouple wire with different depths, which differences depth of the thermocouple wire end was 5 mm as shown Fig. 5.

For each test, the pulse velocity and the concrete strength were measured follow the specification of SNI 03-4802-1998 (ASTM C597) and SNI 03-3404-1994 (ASTM C39). For comparison, unheated five of the cylindrical specimens were also tested.

The UPV instrument, which branded TICO, is portable and simple to operate. The UPV consists of two transducer 54 kHz that is completed integrated software for transmission of the measured value to PC and has capacity pulse rate 3/s, memory for up 250 measured values.

For the residual compressive strength by destructive testing were tested to the specification of testing drilled core of concrete. For each of the wall panel specimen was taken three core samples after 7 days furnace cooling.

Figure 4. Temperature measuring points for wall specimens[20]
3. Result and Discussion
There is no doubt that when concrete is exposed to elevated temperature, such as fire, there is significant reduction of compressive strength. The residual strength is also depending on many factors such as exposure time, side exposure of fire, properties concrete, etc. The interdependence of these factors is difficult on an accurate model.

| Table 3 | Comparison of the residual strength between 1-side and 3-side exposure of fire based on destructive test [20] |
|---------|------------------------------------------------------------------------------------------------------------------|
| No. specimen | Time elapsed heat | Compressive strength (MPa) | Ratio reduction (%) |
| CT₀      | 0                  | 19.046                       | 0                  |
| CT₁      | 1 h                | 9.285                        | 51                 |
| CT₂      | 2 h                | 3.729                        | 80                 |
| W₁T₁     | 1 h                | 12.578                       | 34                 |
| W₂T₂     | 2 h                | 11.573                       | 39                 |

| Table 4 | Comparison of the ultrasound velocity wave based on UPV test direct method [20] |
|---------|-----------------------------------------------------------------------------|
| No. specimen | Time elapsed heat | Velocity (m/s) | Ratio reduction (%) |
| CT₀      | 0                  | 3579            | 0                  |
| CT₁      | 1 h                | 1049            | 71                 |
| CT₂      | 2 h                | 616             | 83                 |
| W₁T₀     | 0                  | 1607            | 0                  |
| W₂T₀     | 0                  | 1629            | 0                  |
| W₁T₁     | 1 h                | 1358            | 15                 |
| W₂T₂     | 2 h                | 1237            | 24                 |
3.1. Residual concrete strength

Table 3 and table 4 show the result of comparison time elapsed exposure and side exposure to residual strength concrete and ultrasound velocity. The One-side exposure specimen represent for the wall specimens and the 3-side exposure specimen for the cylindrical specimens. The cylindrical specimens were subjected to heat at the same time with the wall specimens.

The residual strength ratio obtained by dividing the residual strength by the original strength. The experimental result in Table 3 shows that time exposure of fire has a significant influence on the residual strength recovery. In case of the residual strength ratio exposed for 1 hour heated can be increased from 51% to 80% for 2 hour heated for the cylindrical specimens. The ratio strength reduction for The wall specimens from 34% to 39% for 2 hor heated.

The experimental result also shows the influence of side exposure of fire. The residual strength for 3-side exposure lower that 1-side exposure. These result is expressed to % of the ratio reduction for the cylindrical specimens lower than the wall specimens. For 1 hour heated, the experimental result for 3-side exposure has 51% and 34% for 1-side exposure. Clearly, it was observed that increasing number of the side-exposure of fire has significant influence to decrease of the residual concrete strength.

These experimental results have trend similar for the ratio reduction based on UPV testing used direct method as shown in Table 4. For the 3-side exposure as well the 1-side specimens, the ratio reduction based on the UPV velocity measurement increase due to longer of the time exposure fire. For the 3-side exposure, the ratio velocity reduction for 1 hour heated was obtained 71% increased to 83% for 2 hour heated.

The UPV velocity ratio for the 1-side specimens was obtained by dividing of difference of the UPV velocity of the unheat specimen to the UPV velocity heated is divided by the velocity of the unheat specimen for same of the wall specimens. Effecting of time exposure of fire has same trend to the result of the 3-side specimens. For 1-side exposure, the ratio reduction velocity increase from 15% to 24% for 2 hour heated.

3.2. Depth of concrete damage layer

Measurement of the ultrasonic velocity has the advantage of a NDT technique able to differentiate among damaged and non-damage zones. The depth of the damage concrete layers was obtained based on only the wall specimens due to damaging of the cylindrical specimens have occurred into whole thickness of the specimens.

The pulse velocity through the upper layer or the damage concrete (V1) and and the lower layer or the sound concrete (V2) will be indicated on the plot by the different slopes of the two straight lines fitted to the data. The set of pulse velocities were obtained from the UPV travel times that was measured in different distance between transmitter and receiver transducers through indirect method, as shown in Figure 6.

![Figure 6](image)

Figure 6. Use of indirect method to determine depth of deterioration [12].
Each of the wall specimen was measured on 3 areas in obtaining the set of indirect pulse velocity. The length path of transmitter-receiver transducers differ distance 50 mm, the length path (X) from 100 mm up to 400 mm. The area locations of measurement on the specimens shows in Figure 7 [20].

![Figure 7. Three areas use to determine distribution of pulse velocity through indirect method [20]](image)

Figure 8 shows the travel time as a function of the separation distance length between transmitter and receiver. For the wall specimen which was heated for 2 hour (W2T2) the travel time reaches a longer time than the another specimen (W1T1). This result indicates that the concrete quality of the wall specimen W2T2 has occurred deterioration quality due to subjected a longer heated.

![Figure 8. Transit time as function length path waves](image)

The change in the slope line of each the transit time-distance curve is plotted to estimate the depth of damage concrete layers. Figure 9 and Figure 10 are the slope of the pulse velocity for the wall specimens W1T1 for Figure 9 and the specimens W2T2 for Figure 10.
Figure 9. The slope change along the pulse velocity line for the wall specimen W1T1

Figure 10. The slope change along the pulse velocity line for the wall specimen W2T2

Table 5 shows the depth of the damage concrete layer for each the wall specimen which was subjected to a time elevated heat differently. This result was observed that the effect of the damaged concrete layer and the time exposure of fire. For 1 h time heated the damage concrete of the wall specimen reached 47 mm thickness and for exposure 2 hour of fire the other wall specimen W2T2 reached 78 mm thickness. Addition 1 hour of time heating can thicken the damage concrete layers almost 1.5 times.

Table 5 The depth of damage layers base on indirect UPV velocity

| No. Spec. | Length path (mm) | Vd (m/det) | Vs (m/det) | Depth deterioration (mm) |
|-----------|------------------|------------|------------|--------------------------|
| W1T1      | 200              | 2076       | 3226       | 47                       |
| W2T2      | 200              | 815        | 3355       | 78                       |

For exposure temperature above 400°C the compressive strength tend to fall drastically and the residual strength after 800°C exposure may be only 20% of its ambient strength [7]. Base on this research, the depth layer of damage concrete is assumed when temperature of the thermocouples reached 400°C.
Fig. 11 and Fig. 12 show the record curve of the time exposure of fire with heating temperature that was measured with the set of thermocouple was embedded inside of the concrete specimens. Assuming that the concrete layers will be damaged at 400°C temperatures, base on the temperature-time exposure curve is drawn a straight line at a temperature of 400°C to find out at what minute the thermocouple tip reaches a temperature of 400°C. And at the point intersection of the both line will be indicated the thickness of the damage concrete layers. For example for the wall specimen W1 which was heated for 1 hour exposure at TC15, that means the depth of tip thermocouple at 15 mm from top surface of the concrete specimen, for 400°C temperature was reached at 60 minute time of exposure fire. This result indicates that the damage concrete layer was reached 15 mm.

![Figure 11. Distribution of heat temperature as time elapsed for each thermocouple wire inside the wall specimen W1T1](image1)

![Figure 12. Distribution of heat temperature as time elapsed for each thermocouple wire inside the wall specimen W2T2](image2)

Table 6 shows when of the thermocouples reach at 400°C temperature. This measurement was observed to determine the thickness of the damage concrete layer. In case of the wall specimen W1T1 for 400°C temperature reached, was heated up to 35 minutes to get 5 mm depth of the damage concrete layer.
For the specimens W2T2 the damage concrete was reached after 30 minute heated which means faster than the specimen W1T1. These result means the concrete quality of the specimen W2T2 lower and easier damage than the specimen W1T1. The damage concrete.

**Table 6** Time exposure of fire indicates the depth of damage concrete layers

| No. Spec | Elapsed time (minute) |
|----------|-----------------------|
|          | TC_5  | TC_10 | TC_15 | TC_20 | TC_25 |
| W_1T_1   | 35    | 55    | 60    | ---   | ---   |
| W_2T_2   | 30    | 40    | 55    | 70    | 90    |

After heating finish, the damage concrete for the specimen W1T1 was obtained 15 mm thickness for 1 hour of exposure heat and for the specimen W2T2 was obtained 25 mm thickness as long 90 minute exposure of fire. The damage concrete layer for specimen W2T2 may thicker than 25 mm after heating finished.

Comparison the experimental result from UPV measurement by the record of thermocouples data to determine the damage concrete that subjected to high temperature, indicates the UPV measuring is more severe than quantitatif assessment with throughput thermocouples detection.

Although there are several techniques to determine the depth of concrete altered by the temperature, their use alone do not allow accurately determining the depth of concrete affected by the fire, and some of them are not able to discriminate between the type of damage, physical or chemical [3].

4. **Conclusion**

In this study, a series of test were performed to evaluate the change in compressive strength and to determine the depth of damaged concrete subjected to high temperature.

Based on the experimental result, the following conclusions are drawn:

- Comparison of effect the time exposure to the side exposure of fire to residual strength concrete and ultrasound velocity, the result shows increasing number of the side-exposure of fire has significant influence to decrease of the residual concrete strength.
- The deterioration of concrete was observed based on the wall specimens which was subjected to the time elevated heat differently. The experimental is determined by analysis of slope change of ultrasound velocity is compared to thermocouples detect. The UPV measuring indicates the damage concrete more severe than quantitatif assessment with throughput thermocouples detection.
- Measurement of the ultrasonic velocity has the advantage of a NDT technique able to differentiate among damaged and non-damage zones. However, the determination of the depth of concrete is difficult from this method as the ultrasound velocity variation in a fired concrete change not only due to the dehydration of cement paste, but also the presence of crack.

5. **Acknowledgement**

The author wants to thanks The Research for Human Settlements, Ministry of Public Works Indonesia for financial support of this work.
6. References

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