Influence of Aggregate Gradation on the Longitudinal Wave Velocity Changes in Unloaded Concrete

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Abstract. Diagnosis is an important factor in the assessment of structural and operational condition of a concrete structure. Among diagnostic methods, non-destructive testing methods play a special role. Acoustic emission evaluation based on the identification and location of destructive processes is one of such methods. The 3D location of AE events and moment tensor of fracture analysis are calculated by longitudinal wave velocity. Therefore, determining the velocity of longitudinal wave of concrete and the impact of the material and destructive factors are of essential importance. This paper reports the investigation of the effect of aggregate gradation on the change in wave velocity of unloaded concrete. The investigation was carried out on six 150 × 150 × 600 mm elements. Three elements contained aggregate fraction 8/16 mm and the other three were made with aggregate fraction 2/16 mm. Two acoustic emission sensors were used on the surface of the elements, and the wave was generated by the Hsu – Nielsen source. Longitudinal wave velocities for each group of elements were calculated and statistical test of significance was used for the comparison of two means. The results of the test indicated a substantial effect of the aggregate grain size on the change in longitudinal wave velocity. The average wave velocity in the concrete containing 8/16 mm fraction was 4672 m/s. In the concrete with 2/16 mm fraction, the velocity decreased to 4373 m/s. The velocity of the wave decreases at larger quantities of aggregate. The propagating longitudinal wave encounters more aggregate grains on its way and is reflected, also from air voids, multiple times and so its velocity is noticeably lower in the concrete with the 2/16 fraction. Thus, to be able to accurately locate AE events and analyse moment tensor during concrete structure testing, the aggregate grain size used in the concrete should be taken into account.

1. Introduction

Diagnostics and monitoring concrete structures have awakened a growing interest in the area of damage detection. This is caused by changes in the standards and the fact that many construction works are subject to aging in technical terms. What is more, some structures experience higher loads than the maximum design load or their approved service life limit is exceeded. The scope of research [1] conducted in the European Union and the United States has included first and foremost the road infrastructure, emphasising its importance to further development of those countries. For that purpose, modern non-destructive testing methods [2] are employed, including those based on the acoustic methods. One of these methods is acoustic emission [3] based on qualitative and quantitative measurement techniques. The quantitative measurement relies on the registration of wave shapes of acoustic emission signals and the parameters. This method enables interpretation of local damage in
the form of three-dimensional locations and provides information on structural changes in the material through moment tensor analysis. The quantitative approach is calculated based on longitudinal wave velocity [4]. Thus, to obtain accurate results it is essential to determine the influence of the material used on the longitudinal wave velocity.

This paper presents the investigation of the effect of aggregate gradation on the change in longitudinal wave velocity of unloaded concrete. Researchers have assumed [5] that the velocity of longitudinal wave may change depending on the amount of aggregate. In this study, the author confirmed this assumption for concrete elements.

2. The apparatus
To calculate the velocity of the longitudinal wave, the arrival time to the sensors was measured directly. The velocity is the ratio of the distance and the registered time difference between two acoustic emission sensors. The elastic wave was obtained by breaking a brittle graphite lead 0.5 mm in diameter, 3 mm long and 2H grade [6], figure 1.

![Fig. 1. Hsu-Nielsen source](image)

A remote acoustic emission apparatus was used to record the wave propagation. The unit works in the range of frequency response from 1 kHz to 1 MHz. The amplitude threshold was set at 40 dB. The induced elastic wave was received from the object by two sensors with resonant frequency 55 kHz. Figure 2 illustrates a two-channel portable device and sensors for acoustic emission measurement.

![Fig. 2. The acoustic emission apparatus](image)

3. The subject of the research
The test consisted in determining the change in the value of the wave velocity depending on aggregate gradation. The test was carried out on six 150 × 150 × 600 mm elements. Three elements contained aggregate fraction 8/16 mm and the other three were made with aggregate fraction 2/16 mm. Elements were made of concrete class C30/37, cement CEM I 42,5 and limestone aggregate. The sensors no. 1 and 2 were mounted on the surface of each element, spaced at 500 mm, figures 3 and 4. The excitation of the wave was performed four times at each element and twelve times for each group.
4. Results
Longitudinal wave velocities were calculated for each group of elements. Statistical significance test, the paired two-sample t-test, was used for the comparison of the two groups. The groups were normally distributed. The null hypothesis assumes that the population means do not differ. The significance level of p-value for the tested models was assumed to be 0.05. Tables 1, 2, 3 compile the analysis results.

**Table 1.** Statistical measurements of longitudinal wave velocity

| Aggregate gradation [mm] | Amount of data | Mean [m/s] | Standard deviation |
|--------------------------|----------------|------------|--------------------|
| 8/16                     | 12             | 4672       | 31.2               |
| 2/16                     | 12             | 4373       | 93.7               |

**Table 2.** Test of variance equality

| Method     | Numerator - degrees of freedom | Denominator - degrees of freedom | F value | Pr. > F |
|------------|--------------------------------|---------------------------------|---------|---------|
| Folded F   | 11                             | 11                              | 8.98    | 0.0010  |

**Table 3.** T-test

| Method            | Variances       | Degrees of freedom | t value | Pr. > [t] |
|-------------------|-----------------|--------------------|---------|-----------|
| Summary variance  | Equal           | 22.0               | 10.48   | < 0.0001  |
| Satterthwaite     | Unequal         | 13.4               | 10.48   | < 0.0001  |

The hypothesis of equal variances was rejected $P = 0.001$, Table 2. On that basis, you read the bottom line from table 3, unequal variance. P-value is lower than 0.0001, which means that the groups differ in terms of the average wave velocity. The aggregate grain size had an effect on the change in longitudinal wave velocity. The average wave velocity in the concrete containing 8/16 mm fraction was 4672 m/s. However, in the concrete with 2/16 mm fraction, the velocity decreased to 4373 m/s,
Table 1. Figure 5 presents the distribution of average longitudinal wave velocity in terms of aggregate gradation.

![Graph showing wave velocity vs aggregate gradation](image)

**Fig. 5.** Distribution of average wave velocity for aggregate fraction 8/16 mm elements and aggregate fraction 2/16 mm elements.

Figure 6 presents the composition of concrete for each group. Figure 6a illustrates air voids and 8/16 mm aggregate fraction. Figure 6b illustrates air voids and 2/16 mm aggregate fraction.

![Concrete composition images](image)

**Fig. 6.** Concrete composition of elements: a) aggregate fraction 8/16 mm, b) aggregate fraction 2/16 mm.

5. Conclusions

The literature indicates that the amount of aggregate can have an effect on wave velocity in the mortar. The research analyses this problem considering various aggregate gradation. In the concrete with 2/16 mm fraction, the number of aggregate is greater than in the concrete containing 8/16 mm fraction. The results show that the velocity of the wave decreases at larger quantities of aggregate, figure 5. The velocity is definitely lower in the concrete with the 2/16 fraction. The propagating longitudinal wave encounters aggregate grains on its way and is reflected multiple times, also from air voids, figure 6. Thus, the aggregate grain size used in the concrete should be taken into account for accurate location and fracture analysis of events.

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References

[1] L. GOŁASKI, B. GOSZCZYŃSKA, S. GOSZCZYŃSKI, W. TRĄMPCZYŃSKI, “Problems concerning bridges diagnosis as an example of the engineering structures diagnosis”, 55 Konferencja Naukowa KILiW PAN i KN PZITB, Kielce - Krynica, pp. 525-532, 2009.

[2] J. HOŁA, K. SCHABOWICZ, “State of art non-destructive methods for diagnostic testing of
building structures - anticipated development trends”, *Archives of Civil and Mechanical Engineering*, vol. 10, issue 3, pp. 5-17, 2010.

[3] G. ŚWIT, ”Predicting failure processes for bridge – type structures made of prestressed concrete beams using the acoustic emission method”. *Wydawnictwo Politechniki Świętokrzyskiej*, Kielce 2011.

[4] Ch. Grosse, L. Linzer, “Signal-based AE analysis”, *Acoustic emission testing. Basics for research - application in civil engineering*, Ch. Grosse, M. Ohtsu (Eds.), Springer, pp. 53-99, 2008.

[5] E. Landis, S. Shah, “The influence of microcracking on the mechanical behavior of cement based materials”, *Advanced Cement Based Materials*, vol. 2, issue 3, pp. 105-118, 1995.

[6] ASTM E976-10, “Standard guide for determining the reproducibility of acoustic emission sensor response”, 2010.