MODELING THE LOAD-DISPLACEMENT RESPONSE OF CONCRETE WITH MULTI-INCLUSION-CYLINDRICAL AGGREGATES INCORPORATING THE AGGREGATE-DISTANCE EFFECT AND CONFIGURATION

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ABSTRACT

The behavior of concrete is highly influenced by the characteristics of basic materials, i.e., the mortar and the aggregate. Whereas the aggregates generally exhibit linear behavior, the mortar shows a high degree of non-linearity, even at very low stress levels. The ultimate strength and stiffness of the aggregates are also significantly larger than that of the mortar, leading to stress disparities under advanced loading levels. An integrated research including the construction of a Finite Element Model (FEM) and concurrent experimental work was conducted at the *Structural and Material Laboratory, Diponegoro University in Semarang, Indonesia.* This FEM program was designed to analyze the behavior of concrete specimens including aspects such as; *material non-linearity, failure criteria and anisotropic behavior*.

Further research was expanded to study the effect of *aggregate-distance* and *configuration* to the behavior of specimens with multi-inclusions. The presence of multi-inclusions result in *aggregate interaction, mortar confinement and interlocking*, influencing the overall behavior of the specimen. It was found that aggregates arranged *perpendicularly* to the load direction, results in a higher stiffness modulus and ultimate strength, when compared to a configuration with aggregates configured *parallel* to the load direction. Although the distance of the aggregate's centroids did not significantly influence the stiffness behavior, it affects the ultimate strength of the specimen noticeably. The FEM program was accessed to generate the stresses at mid-height, and the energy distribution between mortar and the aggregate was studied. It was found that the configuration of aggregates considerably effect the energy distribution in a specimen.

Keywords: multi-inclusions, finite element modeling, load-displacement behavior, non-linearity.

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1. INTRODUCTION

The behavior of concrete is a complex interaction of the basic material properties. In the past, concrete was mandated as a two phase material consisting of only the mortar and the aggregates, whereas in reality a weak area, the Interfacial Transition Zone (ITZ) exists. A Finite Element Model (FEM) was constructed approaching the concrete as a three phase material, including the ITZ. This program was developed by assuming an independent behavior for the ITZ in tension and shear, and test methods to obtain these load-displacement responses were explored (Han and Nuroji 2010; Han and Sabdono 2011). The program was validated with identical laboratory tested specimens, having the exact same material properties (Han and Purnono 2011, 2012; Han et al. 2012). The program was proven to be a sophisticated tool to analyze aspects such as ultimate strength, structural stiffness behavior, failure mode and energy distribution. Figure 1 shows the load-displacement response produced by the program as compared to the experimental test results, for single-inclusion specimens with variations in inclusion diameter.

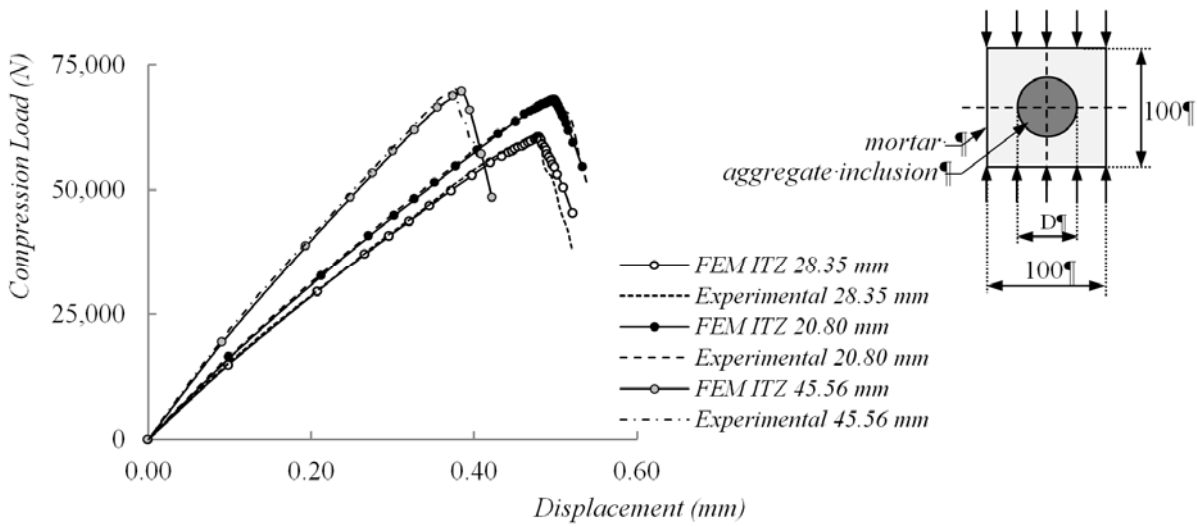

Figure 1: Validation of the FEM Program.

To analyze the response of multi-inclusion specimens, two sets of test model were designed. The first are the specimens with cylindrical aggregates configured *parallel* to the load direction (specimens "SV3 and SV4") having a centroids distance of *d*, and the second with aggregates arranged *perpendicularly* to the load direction (specimens "SH3 and SH4"). The distance *d* had a variation of 30 mm and 40 mm. The inclusion was a *diorite* aggregate with a diameter of 20.8 mm, obtained with a water-cooled diamond core drill. The specimens have a size of 100 x 100 x 50 mm (figure. 2).

The specimens were casted, kept moist and tested at the age of 28 days. For all groups six valid specimens were produced and tested in the laboratory. An all-mortar specimen having the exact same dimension was made and functions as comparison to study the effect of the ITZ. The properties of the aggregate and mortar were tested uni-axially, and used as input for the FEM

program. For all compression testing purposes, doubly greased 100 μm Teflon sheets were placed to prevent the confinement between the loading platen and the specimens.

The testing apparatus was a *Hung Ta HT-8391PC Computer-Controlled Servo Hydraulic* with a loading capacity of 2000 kN. Loading rate was set at 0.25 MPa/second in accordance with the ASTM 339/C39M-05 standard.

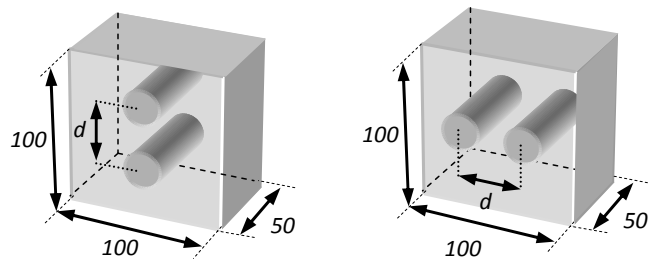

Figure 2: Test Specimen and Aggregate Configuration.

2. TEST RESULTS

The recorded data consist of the stress-strain response of the specimen under uni-axial compression. A visual recording of the loading process was obtained by using a high resolution video camera. The aggregate had a cylindrical compression strength of 159 MPa, with a Poisson's ratio of 0.25 and an initial tangent stiffness modulus of 75 GPa. The mortar properties were measured to be 47 MPa and 32 GPa for the cylindrical compression strength and initial stiffness modulus respectively, while the Poisson's ratio was 0.22.

2.1. The Stress-Strain Response

The stress-strain response of the specimens is shown in figure 3. The dotted points are the experimentally obtained data, while the lines represent the behavior as predicted by the FEM program.

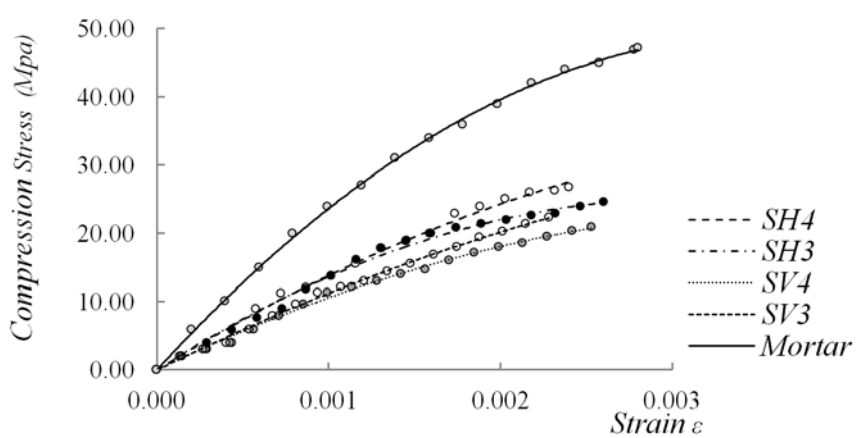

Figure 3: Stress-strain Response of Specimens.

The behavior shows a clearly non-linear response, and the stiffness modulus decreases gradually, as a function of stress increase. After reaching the ultimate strength, a brittle failure is observed. The stress-strain behavior of all specimens including the mortar however, is similar.

The mortar exhibits the highest compression strength, combined with the largest strain at ultimate. Figure 4 demonstrates the comparison of ultimate strength for each specimen.

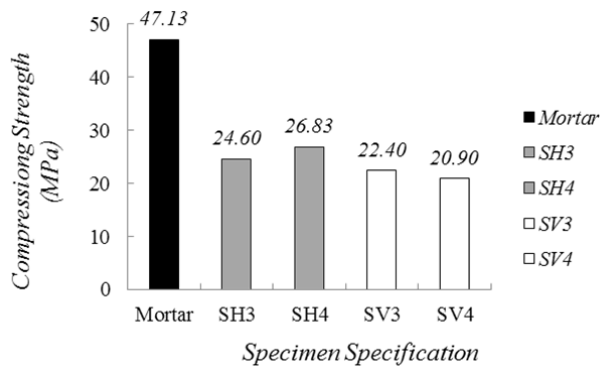

Figure 4: Ultimate Stress Comparison.

2.2. Initial Cracking

The developed FEM program is utilized to study the cracking pattern of specimens. It is shown that for all specimens, regardless the configuration of the aggregates, the failure is initiated at the ITZ in tension. The ITZ nodes in tension are located at the *exact same place* with respect to the inclusion, i.e., at the left and right of the aggregate. This initial ITZ failure is observed at levels of circa 20% to the ultimate strength. At stress levels of around 60% of the ultimate strength, the first Gauss point in the mortar fails due a combination of tensile and compression strains in the principal stress direction. A similar location for all the initial mortar failures were detected, regardless the configuration of inclusions (figure 5)

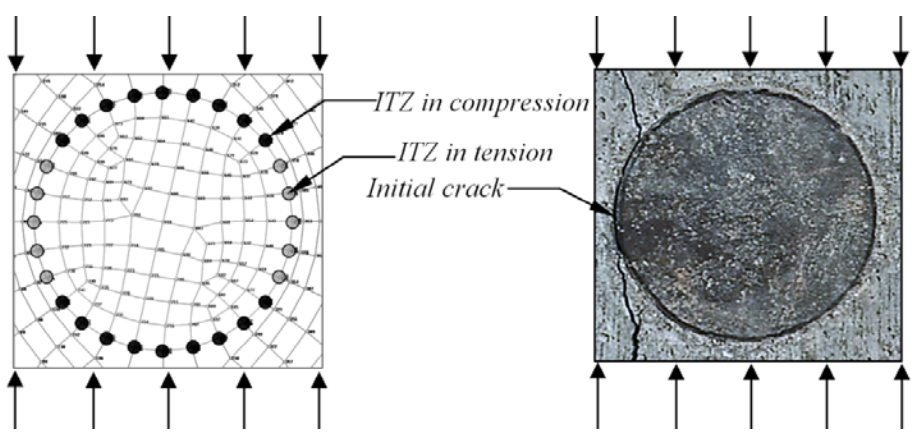

Figure 5: Initial Failure of Specimens.

2.3. Failure Pattern

Observing the general failure pattern, it is shown that cracking starts at the ITZ in tension, and then propagates along the line perpendicular to the most extreme principal tensile strains. The aggregates arranged *perpendicularly* to the load direction resulted in four failure contours, while the specimen with aggregates arranged *parallel* to the load direction resulted in only two failure contours. It is interesting however, that the specimen with the four failure lines performed better than the one with two failure lines (figure 6)

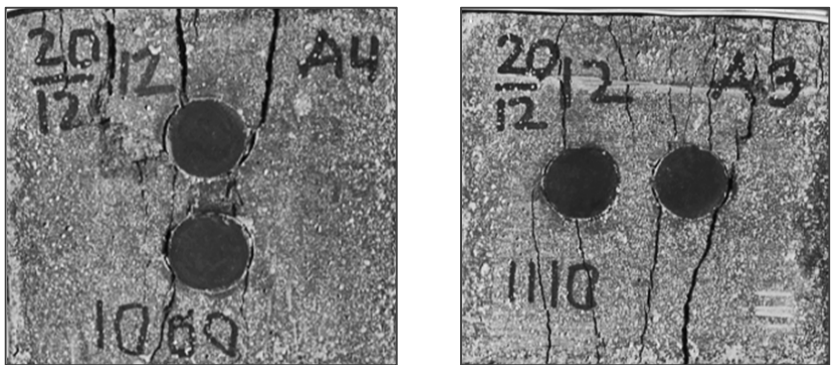

Figure 6: Specimen Failure Pattern.

2.4. Energy Distribution

The program is accessed to determine the stresses at nodal points, extrapolated from the surrounding Gauss points of adjacent elements. Since stress concentrations are high in the vicinity of the ITZ, it is of major interest to study how the inclusion configuration and distance affect the energy pattern. The total energy at mid-height along the horizontal line (σ_{yy}) is calculated from the area of the stress diagram, multiplied by the displacement of the specimen under the considered load level (figure 7). All five specimens are studied for the same vertical uniformly distributed load of 25 kN, and the energy percentage calculated. The results are tabulated in table 1.

Table 1: Energy Distribution of Aggregate and Mortar

	Mortar	SH3	SH4	SV3	SV4
Mortar Energy (%)	100	52.1	53.3	56.6	56.8
Aggregate Energy (%)	0	47.9	46.7	43.4	43.2

The energy is calculated from the formula:

$$u = \int \frac{1}{2} \sigma_{ij} \varepsilon_{ij} dv \tag{1}$$

U is the energy contribution calculated from the stress and strain σ_{ij} and ε_{ij} at nodal points, multiplied by the total volume dv of the mass under consideration.

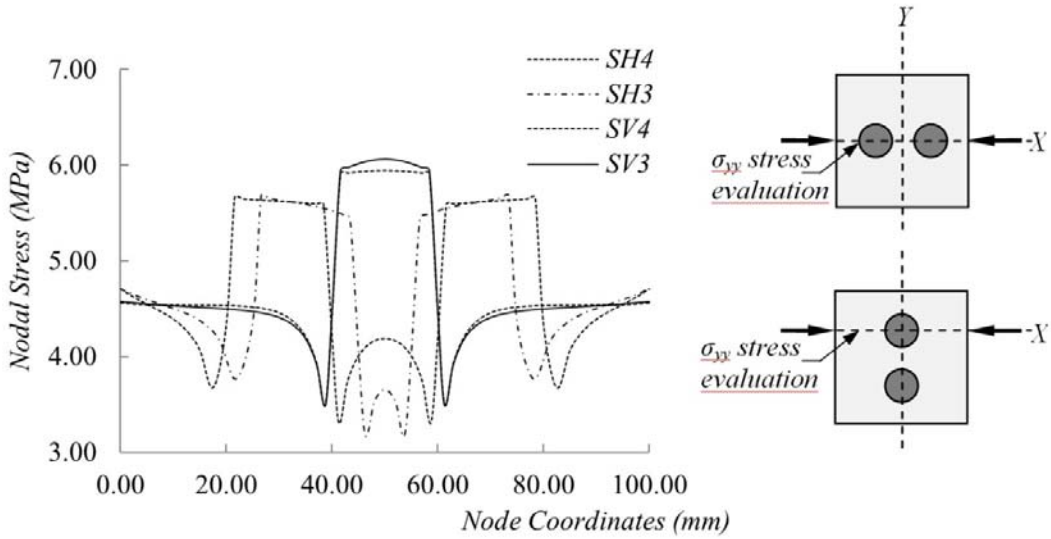

Figure 7: Stress Distribution at Mid-height.

3. DISCUSSION AND CONCLUSION

It is shown that the presence of aggregates results in a decrease of the ultimate strength and stiffness modulus. These findings underline that the ITZ is the weak link in concrete, and that crystal formation in the ITZ will lead to initial cracking. The development of crystals in the ITZ also results in a higher porosity, when compared to the mortar farther away from the aggregate surface. The ultimate strength will decrease around 50% when compared to the mortar specimen.

The specimens SH3 and SH4 with aggregates arranged *perpendicularly* to the load direction, performs slightly better when compared to the specimens with aggregates configured *parallel* to the load direction SV3 and SV4. This can be explained by the high stress concentrations between the two inclusions that results in an earlier failure initiation in the mortar. The specimen SV3 to some extent shows a higher ultimate strength when compared to the SV4 specimen. The explanation lies in the fact that the interaction between aggregates in close vicinity will increase the load carrying capacity. Observing the energy distribution, it can be seen that for SV4 relatively less energy is absorbed by the aggregate. The exact distance at which the interlocking effect will take place, has yet to be determined.

For the specimens SH3 and SH4 no interlocking occurs, since the axes of the inclusions are perpendicular to the direction of the load. Therefor the specimen SH3 will have a *lower* ultimate strength as compared to SH4, due to the overlapping stresses in the mortar between aggregates. The energy contributed from the aggregate for SH4 is therefore also slightly higher. However, placing the inclusions farther apart can result in the *spalling* of the mortar on the left and right sides of the specimen.

Generally, a better performance will be obtained when the energy distribution of the aggregate is higher than the mortar, since the aggregate eventually has a higher capacity in terms of load carrying capacity and stiffness. When the ITZ has a better bond, more of the energy can be transferred to the aggregate, and initial micro crack formation postponed. Artificial ITZ using resin or synthetic agents are among others, options to strengthen the ITZ. Another approach is to fill the voids in the ITZ by smaller, cementitious components such as silica fume, fly ash and nano-particles.

While the developed program deals with the presence of the ITZ in great detail, effect such as interlocking, interrelation and *spalling* should be accounted for. The work conducted at the *Structural and Material Laboratory, Diponegoro University* however, can be used as basic to study the behavior of the effect of multi inclusions to the specimen.

4. ACKNOWLEDGMENTS

The authors would like to take a moment to remember *Mohammad Wahyudi* our student who worked on the experimental research and passed away shortly after completing his study.

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