The Effect of the Interfacial Transition Zone between Aggregate and Mortar to the Overall Performance of Concrete Structures, a comparative study, from micro to macro

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The Effect of the Interfacial Transition Zone between Aggregate and Mortar to the Overall Performance of a Concrete Structure

A comparative study, from micro to macro

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Abstract—**The Interfacial Transition Zone (ITZ) between the aggregate and the mortar in concrete has long been recognized as the *"weak link"* in the material. Research in this field conducted at the *Material Laboratory, Diponegoro University* resulted in the normal-tensile and shear behavior of the ITZ, based on newly developed test methods. The load-displacement response of the ITZ in their normal and shear mode was lucidly explained. At further stages, a Finite Element Model (FEM) was developed modeling concrete as a three-phase, rather than a two-phase material by including the ITZ into the model. The results of this integrated method showed that the ultimate stress as well as the stiffness modulus of concrete is strongly influenced by the ITZ. In this paper a numerical analysis to the effect of these deviations to a multi-storey structure, is studied. The results demonstrated that the ITZ influences the structure's performance significantly. Techniques to improving the ITZ in concrete can therefore have a positive impact on the overall structural behavior.**

Keywords-component; ITZ; Finite Element; Stiffness Modulus; Load-displacement response

I. INTRODUCTION

As early as 1956 it was found that the area adjacent to the aggregate surface differs both mineralogical as well as micro-structural, from the mortar farther away from the aggregates. This area has a higher porosity degree in combination with large calcium hydroxide crystals, having a preferential orientation that initiate crack propagation along its weak plane, following the *Van der Waal* plane of forces.

Since this Interfacial Transition Zone (ITZ) is very small, only 30 to 50 μm in thickness, direct methods to obtain data concerning its behavior are not readily available. Through the years, extensive research has been conducted to test the ITZ, and more recently a new method was developed at the *Material Laboratory, Diponegoro University in Semarang Indonesie* [4], [6]. These test methods provide information regarding the load-displacement response of the ITZ both in normal-tension and in shear, as well as its ultimate loading capacity.

A Finite Element Model (FEM) incorporating this ITZ was then constructed. The load-displacement responses and additional information relating the ITZ were functioning as input to the model. Other input parameters required by the FEM are the mechanical properties of the mortar and the aggregate; modulus of elasticity in uniaxial compression (E), the Poisson's ratio (υ) and their stress-strain relationship (σ-ε). In the model, the ITZ is simulated as a linkage element having two springs, one perpendicular to the aggregate surface representing the normal behavior, and one parallel, corresponding to the shear response. The springs have a zero length, and by designating double nodes having exact identical initial coordinates at the border of the aggregate, the movement of the ITZ is simulated by these springs.

The FEM produces the load-displacement relationship of the concrete, including the effect of the ITZ. The resulting data were further transformed to the stress-strain relationship, so that the stiffness modulus and the ultimate stress of the concrete were obtained. When the FEM program is ran assuming a perfect bond, an evaluation on the effect of the ITZ is accomplished. The resulting data are then used to analyze the effect of the ITZ to a two-storey concrete building designed in accordance to the Indonesian Building Code (SNI).

II. EXPERIMENTAL TESTING OF THE ITZ

A. *Normal Tension Response*

To study the behavior of the ITZ in the normal-tension direction, an experimental model is constructed which targets only the ITZ normal response. The *Dyna Proceq haftprufer pull-off tester Z16* (Fig. 1) having a pull-out capacity of 16 kN is used.

The pull-off tester has an accuracy level of 2% with a stroke of 3.5 mm. A cylindrical aggregate is placed on top of the mortar matrix. The specimen is kept moist for 28 days. The specimen is then bounded to a 50 mm *aluminum* test disc using a synthetic bonding agent, and the disc is connected to the apparatus while ensuring a concentric load.

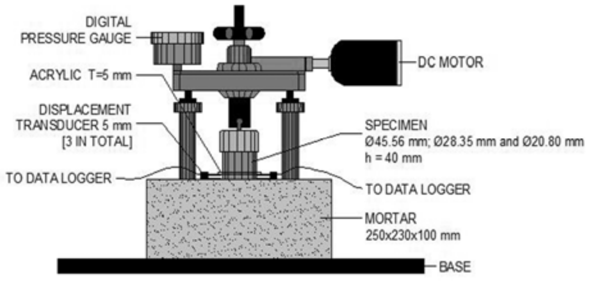


Figure 1. Normal -tensile response testing of the ITZ.

The aggregate is pulled-off by the tester, the load increment measured, and the displacement recorded using three displacement transducers (type UB-2) produced by *Tokyo Sokki Kenkyujo*. These LVDT's have a sensitivity of 2500x10^{-6} strain/mm and a capacity of 2 ~ 4 mm. The LVDT's were positioned at 120 degrees by attaching a sufficiently rigid acrylic ring 5 mm in thickness around the aggregate, and a small base plate to avoid data miss interpreting due to deformation of mortar under the pressure of the clip.

The data from the tests were generated into load/area (in N/mm^2) to displacement (in mm) graphical plots. This approach was chosen since the stiffness modulus can be represented by this particular relationship, and further used as data for the FEM. Also, conversion of displacement to strain requires determining an effective gauge length which is not available with the testing method.

The load–displacement relationship for ITZ normal response is a polynomial to the second degree (Fig. 2). The curves show a distinctively non-linear behavior, even at very low loading levels. The ultimate occurred due to bond failure in the ITZ. The first derivative to the function, for a given spring displacement, defines the tangent stiffness of the slope.

The test results were conducted using local aggregates classified as *porphyritic andesite* and recognized as *Diorite.* This type of rock has a compression strength of 180 to 300 MPa, a stiffness modulus ranging from 70 to 100 GPa and a Poisson's ratio of 0.25. The mortar has a Young's modulus of 32 GPa, a Poisson's ratio of 0.22 with an ultimate cylindrical compression stress of 33 MPa. The "disturbed" is a result of a diamond water cooled sawing procedure.

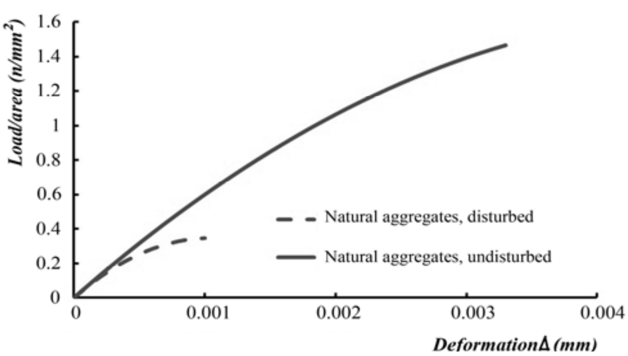


Figure 2. Load-displacement response of the ITZ in tension.

B. Shear Response

To obtain the interface shear stiffness modulus, an aggregate was partially embedded into the mortar mass with only two opposite faces attached to the mortar, simulating bond (Fig. 3). The other two faces are prevented from bonding to the mortar by means of *150 μm Teflon layer*, to ensure only two bonded areas with the mortar.

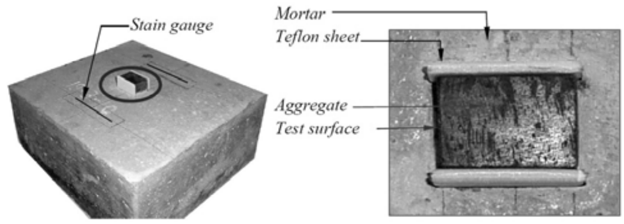


Figure 3. Shear response testing of the ITZ.

The apparatus used is originally a *Control 20063c tile testing equipment* that has a displacement controlled, upward loading platen movement. Since the apparatus has a stable sturdy frame with an adjustable loading platen, it is suitable for the intended test. Displacement is monitored by four LVDT's and the applied force by a load cell, both connected to a data logger.

The aggregate is pushed *downwards* towards the mortar. The incremental force is recorded. Two strain gauges were placed on top of the mortar, perpendicular to the bonded surface, to monitor the confinement effect. All specimens were kept moist up till testing at the age of 28 days.

The load – displacement relationship for the ITZ shear response is a *bi-linear* function, the first part representing the modulus as a contribution of adhesion and friction, and the second being purely the result of friction. Linearity in shear was confirmed earlier by former researchers in this field of study (Fig.4).

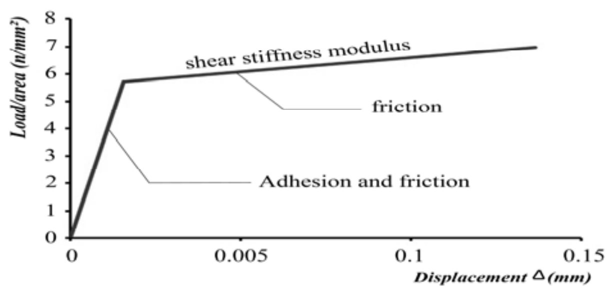


Figure 4. Load-displacement response of the ITZ in shear.

III. FINITE ELEMENT MODELING INCLUDING THE ITZ

The mortar and aggregate are modeled as a four-node, isoparametric quadratic quadrilateral element having 2 by 2 Gauss points. The ITZ is represented by a linkage element with a double spring system. Each node of the system has two degrees of freedom, and the model is constructed as a 2D, plain stress structure. The structural stiffness matrix is an assemblage from the individual stiffness matrices of the Gauss points, and the linkage element, based on the degrees of freedom nomenclature. To access the nonlinear nature of the structure, the arc-length iteration is chosen. This method has the advantage that the post peak curve can easily be approached.

A. Material Behavior, Mortar and the Aggregate

The mortar has a non-linear behavior, and the effect of biaxial strain and effects such as confinement and strain softening are accounted for in the model. The mortar constitutive stress-strain relationship is approach by the *CEB-FIB (2010)* model code [3]. The stiffness modulus in the principal strain coordinate system as a function of the existing strain is accessed by the tangent stiffness method. To accommodate for negative values of the [E] the matrix expression as proposed by *Chen and Saleeb* [2] is used.

$$[E_P]=\begin{bmatrix} \lambda\frac{E_1}{E_2} & \lambda\upsilon & 0 \\ \lambda\upsilon & \lambda & 0 \\ 0 & 0 & G \end{bmatrix} \qquad (1)$$

$$G=\frac{E_1E_2}{E_1+E_2+2\upsilon E_2} \text{ and } \lambda=\frac{E_1}{\frac{E_1}{E_2}-\upsilon^2} \qquad (2)$$

The failure mode of mortar is either due to crushing or cracking of the material. Crushing will occur when both principal strains are in compression, and cracking is typically a characteristic of tension failure. Especially for the later, the material in the direction of the minor principal strain still possess a degree of stiffness. To accommodate the condition after cracking, the material is approached by the orthotropic theory.

Nonlinearity for the biaxial compression case is introduced by the nonlinearity index β [8] derived from the failure envelope in the octahedral plane. The stiffness modulus is a function of β and the second invariant of the deviatoric stress tensors J_2. Research has shown that the confinement produced by the biaxial stresses, will increase the capacity of the material by 20%. A combination of compression and tensile strains in advance to cracking will result in a decrease of the stiffness modulus in the principal compression direction [9]. The stiffness modulus in compression is updated as a function of principal strains.

As for the aggregates properties it was shown that stress-strain response is relatively linear, and a constant value for the stiffness modulus is assumed throughout the loading stages. Further, it is known that the aggregate has a very high ultimate compression strength, as compared to the mortar. In the FEM is assumed that failure will not occur in the aggregates.

B. The ITZ, Normal and Shear Behavior

The ITZ is constructed as a linkage element having four degrees of freedom, two at the aggregate element node, and two at the mortar (Fig. 5)

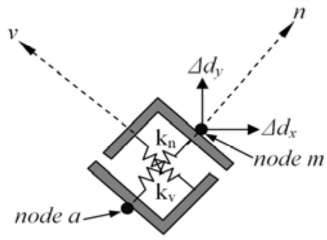


Figure 5. The Double Spring Linkage Element.

The stiffness of the springs k_n and k_v are obtained from the laboratory tested specimens as explained in the former chapter. Since the load-displacement responses are expressed as load-per-area to displacement, the values from these curves should be multiplied by the average length of the two connecting elements, and the thickness of the specimen.

The load-displacement relationship of the spring is expressed in the local coordinate system. This system is demarcated at the bisection line of the angle between the two ITZ surfaces. The positive normal direction is *always* assigned outwards from the aggregate to the mortar, and the positive shear direction follow the right-hand rule. The stiffness matrix in the local coordinate system should therefore be transformed into the global coordinate system, based on the rotation angle. The spring is considered active only when the normal spring is in tension, when in compression a full bond is assumed, and the two nodes of the link act as one.

To enable the linkage nodes to displace, a mesh generator that with the ability to create double nodes, is required. The technique used is to assign an equal number of elements to the mortar and the aggregate at the ITZ location. The FEM program recognizes the ITZ when double nodes are present. The load-displacement relationship for the ITZ is:

$$[\Delta P]=[R^T]\begin{bmatrix} k_n & 0 & -k_n & 0 \\ 0 & k_v & 0 & -k_v \\ -k_n & 0 & k_n & 0 \\ 0 & -k_v & 0 & k_v \end{bmatrix}[R][\Delta D] \qquad (3)$$

Theoretically, the values for k_n and k_v will run from infinite for a full bond condition, to zero for a gap or no bond. The real behavior lies somewhere in between. The experimental test results suggested that a rough aggregate surface will result in a better ITZ performance, while bleeding influences the ITZ negatively. Attempts to improve the ITZ quality include the use of silica-fume, fly ash and most recent, the use of nano-particles.

The FEM was validated to laboratory tested specimens having identical material properties and geometric data. An automatic increment algorithm in combination with the *Current Stiffness Parameter* introduced by *Bergan* [1], was proven to be very effective in improving the performance of the FEM program. A schematic representation of the overall FEM program in handling the material and ITZ is presented in the diagram below (Fig. 6).

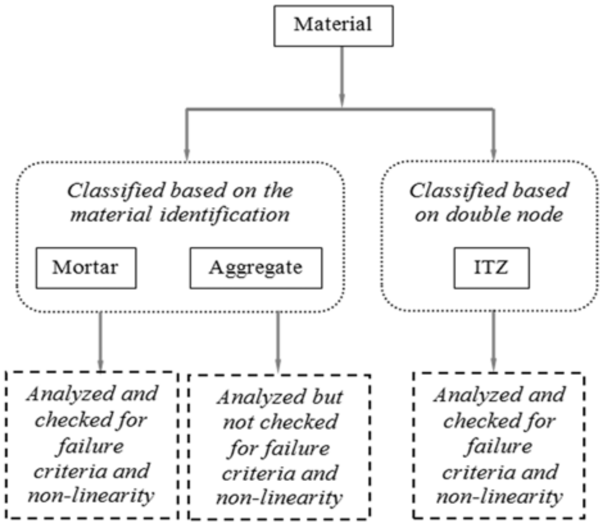


Figure 6. The Double Spring Linkage Element.

IV. VALIDATION SPECIMENS AND TESTING

The FEM model is further validated to laboratory tested specimens to determine its accuracy and correctness. The calibrating specimen is a 100 x 100 x 50 in size with a single cylindrical inclusion placed at centre point. The model was run for specimens with variations in diameter (Fig. 7). Further, a sensitivity analysis was conducted, to evaluate the response of the FEM to the loading rate and meshing pattern [5], [7].

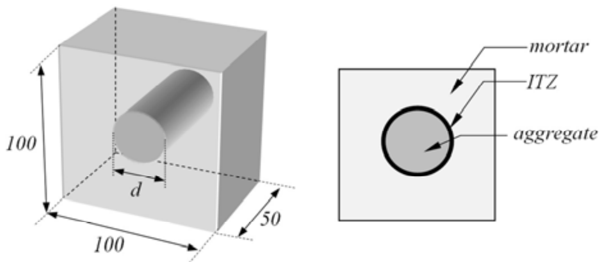


Figure 7. Validation Specimen.

The mold was constructed from *jati* wood and made leak proof using a sealant at the seams (Fig. 8). Further, the cast was covered with a thin layer of bearing grease to ensure waterproofing and to prevent the mortar from attaching to the mold. Aggregates were placed in the designated holes and the mortar was poured surrounding the aggregates. Since the aggregates were positioned vertically, the effect of bleeding can be eliminated. The specimens were taken out of the mold after 24 hours, and cured by the submerging in water.

Before testing, the specimens were dried and leveled to obtain a smooth, flat and leveled surface using a *spirit/bubble level*. Two 100 μm *Teflon* layers were placed on top and at the bottom of the specimen, and the loading increment was set at a rate of 1800 N/s in accordance to ASTM 109/C 109M-02 *Compressive Strength of Hydraulic Cement Mortars*. The load – displacement response was recorded by the *Hung Ta, HT-8391PC Computer-Controlled Servo Hydraulic* compression apparatus having a loading capacity of 2000kN.

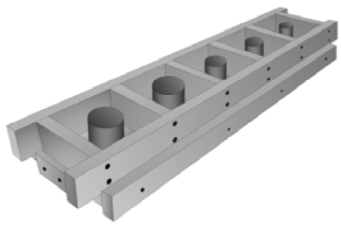
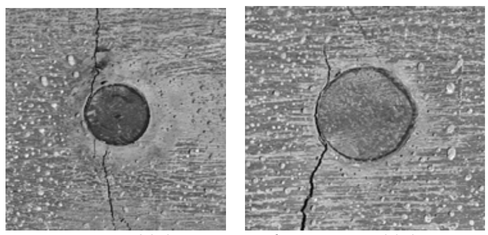


Figure 8. Casting of Validation Specimens.

The load-displacement response of all single aggregate specimens follow a similar pattern, while the cracking propagated during testing was as predicted based on the FEM analysis. This pattern was consequently shown for all variations in diameter. Fig. 9 shows the crack propagation of the aggregates in the mortar matrix, prior to failure of the specimen, the ITZ in tension initiates the failure process. It can be seen that all specimens have a substantial gap at the ITZ in the tension region.



a. Diameter 20.0 mm *b. Diameter 30.0 mm*

Figure 9. Specimen's Cracking Pattern.

V. CONCRETE STIFFNESS MODULUS

When the FEM program was proven accurate and correct in predicting the load-displacement response of the given specimen, these curves can easily be transformed to the stress-strain relationship. In practice, the aggregates used in conventional concrete have a dimension ranging from 10 mm to 30 mm; the model with a 20.0 mm inclusion is therefore the best representation to concrete in practice.

While in reality a perfect bond can never be achieved, the FEM program can be used to create the hypothetical stress-strain response of a concrete mass with a perfectly bonded ITZ (Fig. 10). The Young's modulus for the concrete *including*, and *without* the ITZ is used as input for the analysis using the SAP 2000 program. This program accommodates the geometric nonlinearity of the structure, but assumes a constant stiffness modulus throughout the loading process.

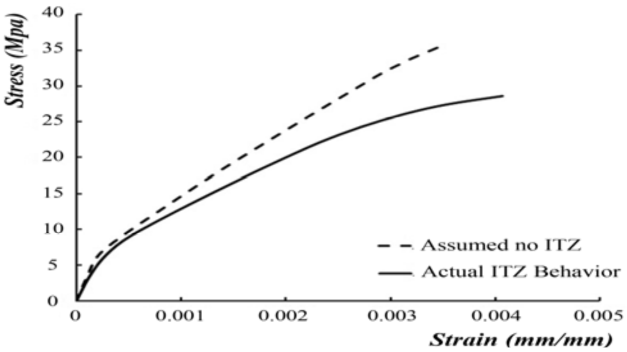


Figure 10. Stress-Strain Relationship of Concrete Including the ITZ.

The concrete with a fully bonded ITZ has a Young's modulus of 29.6 GPa as compared to 23.6 GPa for the specimen *with* the ITZ. The ultimate compression stress is measured 35.8 MPa for the full bonded type, and 28.6 MPa for the ITZ specimen. It is seen that the Young's modulus as well as the ultimate strength deviates 25% from the model with the incorporation of the ITZ. Al higher stress levels, the influence of the ITZ to the stiffness modulus becomes more pronounced.

VI. Analysis of the Effect to a Concrete, Multi-story Building

The structural analysis of a two-storey building is modeled as a 2D frame element, and executed by the SAP *(Structural Analysis Program)* 2000. The structure is subjected a dead load originating from the self-weight of the structural components, wall and cladding, and floor-work. The live load is taken as 300 kg/cm^2 in according to the *Indonesian National Building Code 1987*.

The building is assumed to be located in the *Semarang Area, Central Java, Indonesia* and seismic responses are analyzed based on the code [10]. The seismic region is therefore categorized as region 2 (Fig.11)

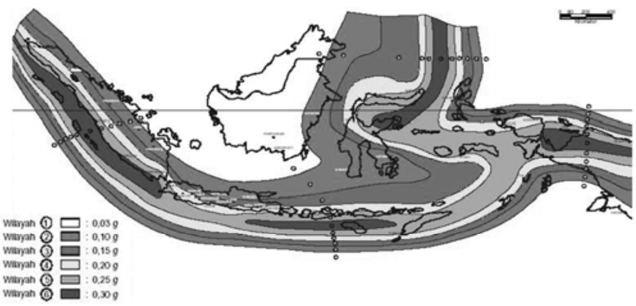


Figure 11. Indonesian Seismic Regions.

The natural vibration time for this zone is 0.285 seconds, so that the horizontal seismic load can be calculated based on the total weight of the structure. The prototype building has a floor to floor height of 4.00 m, and an area of 36 m^2. The beam-to-column connections are rigid and the beams have a dimension of 400 by 600 mm, with columns 400 by 400 mm in size. The frame width and column distance is set at 6.00 m.

The prototype is analysis twice, one time using the material properties assuming a full, perfect bond in the ITZ, and another based on the stiffness modulus properties including the ITZ. The results were compared.

A. Horizontal Deflection and Internal Energy

The actual horizontal load acting on the most top fibers of the building is calculated to be 17.73 kN. Since the SAP 2000 assumes a constant stiffness modulus, the deformation response is linear. However, the resulting data are highly informative. Fig. 11 shows the load-deflection response of the building measured at the top floor.

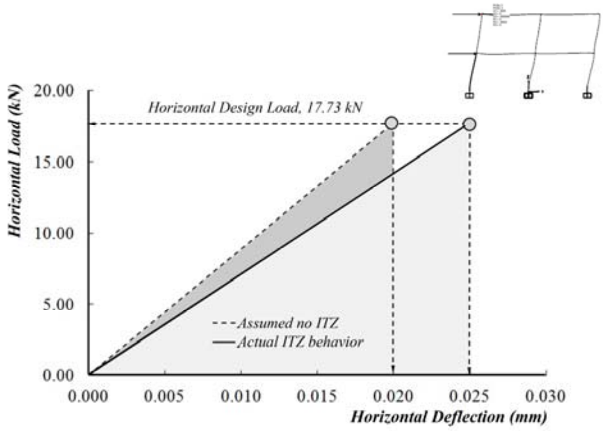


Figure 12. Horizontal Load-Deflection Response.

The presence of the ITZ resulted in a more ductile behavior, the ratio of ultimate deflection between the models *including* the ITZ to the one assuming a perfect bond is 1.25. Since the deviation of the material's stiffness modulus' increases progressively as a function of stress (see Fig. 10), it can be predicted that at higher stress levels, this ratio will increase accordingly.

To study the energy produced by the system, the area under the load-deflection curve was calculated. The model assuming no ITZ resulted in a total internal energy of 17.73 kNmm, while the model with the ITZ yielded in an energy level of 22.16 kNmm. The energy absorbed by an imperfect ITZ thus counts for 20% of its total structural energy.

B. ITZ Improvement and Its Advantage for the Overall Strcuture

It is shown that although usually ignored in the analysis and design of structures, that the ITZ is indeed the weak link in the concrete, and that its behavior significantly influences the response of a structure under combined horizontal and vertical loading.

Since the ITZ is proven to influence the stiffness modulus of concrete, the impact to the structural behavior is predominantly affecting the internal energy and ductility of a structure. The preliminary analysis demonstrated that the deviations are substantially large, even when material nonlinearity and second order behavior is not accounted for.

To dated, numerous techniques and methods are developed, to not only improve the overall concrete behavior, but also to stabilize the ITZ between the aggregate and mortar. Method involving fly ash and silica fume are among the widely known. More recent, the area of nano particles are studied extensively, it was shown that the nano particles could fill the micro gaps in the ITZ. The biotechnology is on the other hand, attempting to create bacteria that produce micro calcium deposits. When entrapped into the water film surrounding the aggregate; these bacteria can overcome the high porosity levels in the ITZ. Major work in this field of study is conducted at the TU Delft, the Netherlands.

VII. Field Study and Retrospective View

Recent field investigation conducted at a multi-storey government building in the Central Java area, resulted in compiling evidence to the contribution and negative effects of poor ITZ on the overall structural behavior. During its use, the building showed less load carrying capacity then was designed for, by the engineers. Cracks in areas subjected to high stress concentrations initiated an in-depth survey to the existing quality of the concrete.

By performing a series of non destructive testing using the a *digital Smith hammer*, and a sample study using SEM *(Scanning Electron Microscope)* readings, it was found that at the location of cracks, the bond between the aggregate and mortar was broken (Fig. 13).

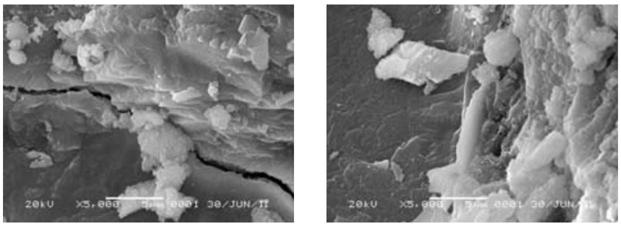


Figure 13. SEM Readings of Failed and Un-cracked ITZ.

The main source of this poor performance in the interface is the fact that during mixing and placing, the field-workers favor to add more water than was required by the mix design analysis, since a better workability will make the placing work easier. The excess water will develop a film surrounding the aggregate, and upon evaporation of which, will leave a gap where weak crystals develop. Further, these weak crystals will result in a higher porosity degree in the ITZ. Another negative effect of the extra water is the bleeding effect on the upper surface of the aggregates, intensifying the weakness in the interface at these areas. The figure on the left shows the SEM reading of the aggregate-to-mortar interface taken at a location of un-cracked concrete, whiles the picture on the right demonstrates the gap created by the failure in the weak interface.

The field investigation proved that a poor interface not only results in a reduction of the material's stiffness modulus, but also leads to crack initiation in this area. Under progressive loading, these cracks will propagate and reduce the performance and overall load carrying capacity of the structure. For the above mentioned case, the *Diponegoro University Team* advised the application of retrofitting by grouting, to fill the cracks and create a better bonding in the interface. An alternate solution is reinforcement of the structural element using FRP wrapping.

VIII. Discussion and Conclusions

From micro to macro. As it sometimes seems, is the micro level in concrete far from connected to a structure. However, research work conducted at the *Diponegoro University, Semarang Indonesia* illustrated that the micro behavior can have substantial effect to the structure in general.

The techniques combining the experimental results with a development of a FEM that amalgamates the ITZ, demonstrated that the ITZ condition has a noticeable influence to the behavior of concrete under combined loading. The preliminary analysis incorporating the ITZ behavior into a building, further established that a poor ITZ will result in a deviation in its ductility and energy response.

More tests models are required to obtain a more detailed outcome, from which an integrated conclusion could be drawn. Also, non linearity of the material as a function of increasing load, have to be included in the analysis. For this purpose a wide range of software are available.

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