Fracture Mechanics of Concrete and Concrete Structures -
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Interfacial shear bond strength between old and new concrete

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ABSTRACT: To better understand bonding mechanism at the interface between old and new concrete surfaces, overlaid specimens were fabricated to measure shear bond strength. Old concrete cubes with two different moisture conditions (saturated surface dry (SSD) and air dry) were chosen. Three different materials with two w/c ratios and a silica fume addition were used for new overlay concrete. From the shear tests, it was found that silica fume in new concrete significantly increases not only the compressive strength of new concrete but also the shear bond strength at the interface. New concrete with low w/c ratio resulted in high compressive strength but lower shear bond strength for both surface conditions compared to high w/c ratio. For all overlay concretes it was consistent that SSD surface condition resulted in much higher bond strength compared to air dry. SEM and XRD were employed to characterize material at the interface and to determine interfacial zone.

1 INTRODUCTION

According to the 2009 Report Card of American Society of Civil Engineers (ASCE), the grade of America's Infrastructure was averaged to a "D", due to a limited capacity and poor quality of old deteriorated infrastructure. The total investment necessary for five-years was estimated as 2.2 trillion dollars. (ASCE, 2009) To enhance the capacity and quality of America's infrastructure by overlaying or patching with rehabilitation materials, it is essential to understand the mechanical properties and behavior at the interface between old construction material and new rehabilitation material: the interface is the weakest link for composite behavior and a source of premature failure.

Bonded concrete overlay is a viable option to increase structural capacity and/or improve ridability of concrete bridges and pavements. With property mismatch of new overlay concrete to old concrete however, bonded concrete overlays may lead to early age failure and a shortened service life. To better understand bonding mechanism at the interface between new and old concrete surfaces, it is essential to measure bond strength at the interfacial layer and to investigate affecting parameters of its properties.

The interfacial layer between old and new concrete usually has different aggregate/cement contents, w/c ratio, and temperature evolution during the curing period compared to the other sides of old construction material and new rehabilitation material. The composition of the interface is affected by w/c ratio of rehabilitation material, surface moisture conditions, bonding agents, and other environmental conditions. The interfacial layer is considered to have similar characteristics to the interfacial transition zone (ITZ) between aggregate and hydrated cement paste. The ITZ between aggregate and paste is weakened due to the "wall effect" where less calcium-silicate-hydrate (C-S-H) particles are present. The structure of cement paste in ITZ is quite different from that of the bulk paste further away from the physical interface in terms of morphology, composition, and density. The ITZ, typically 20-40 μm thick, has less C-S-H particles, greater connentration of ettringite, and higher porosity. (Mindess et. al. 2003)

The bond strength at the interface is affected by the surface and moisture conditions of the existing concrete surface. Several controversies still exist on the effects of bonding agent and moisture conditions of the substrate. Using the results of seven site survey projects, Gillette concluded that bonding agents increase bond strength of two layers. (Gillette 1963) Felt used experimental tests and site surveys to find that a good bond can be achieved without using a grout layer. (Felt 1956) However, he pointed out that the chances of increasing bond strength are improved by using grout. It is also not clear how the bond strength is affected by the moisture condition of the old pavement just before placing overlay concrete. Gillette found that free water on the surface weakens the bond strength. (Gillette 1964) However, Pigeon and Saucier concluded from their tests that moisture condition does not affect bond strength (Pigeon & Saucier). According to Austin et. al, saturated surface dry (SSD) condition is most favorable for higher bond strength. (Austin et al. 1995) These different results might be attributed to the differences in materials for overlay and substrate, environmental conditions, and testing methods.

Several efforts have been made to understand interfacial bond between two materials. (Paramasivam et al. 2002, Davalos et al. 2005) While the macro-mechanical behavior of bonded structures are well established, selection of bonding materials and design details are needed further study. (Ueda & Dai 2005)

Many entities currently use supplementary cementitious materials (SCM) in the construction of Portland cement concrete (PCC) structures to reduce the construction cost and the carbon footprint by utilizing byproducts of other industries. With improved properties of PCC containing SCM, it is desirable to use the SCM in bonded concrete overlay. To improve the mechanical properties of interfacial layer, it is suggested to add 10%-15% silica fume by the weight of cement (Monayez et al. 2004). The addition of silica fume reduces the large pores and eliminates the growth of calcium hydroxide, which is relevant to improve interfacial properties between old and new concrete layers.

2 RESEARCH SIGNIFICANCE

The infrastructures within the states of the US are suffering damages by increased and unpredictable loads. To repair damaged infrastructure and enhance the structural capacity, bonded overlay and/or patching with new construction materials are constructed. To successfully practice the rehabilitation, it is essential to better understand the mechanical behaviors at the interface between new and old concrete surfaces. The findings of this research can be directly adapted in the rehabilitation of concrete pavements and bridges.

3 EXPERIMENTAL STUDY

3.1 *Study parameters*

Three experiment parameters were used to better understand the interfacial properties of overlaid concrete, including moisture condition of old surface and w/c ratio and silica fume content in new concrete as shown in Table 1. SSD and air dry (AD) conditions were made on the old concrete surface to study how the bond strength is affected by the moisture condition of the old concrete.

Table 1. Test Matrix.

Specimen Set	Moisture condition at the old concrete surface	Water to cement ratio of new concrete	Supplementary cementing material
SSD-0.6	SSD	0.60	none
SSD-0.45	SSD	0.45	none
AD-0.6	air-dry	0.60	none
AD-0.45	air-dry	0.45	none
SSD-0.45SF	SSD	0.45	silica fume
AD-0.45SF	air-dry	0.45	silica fume

The compressive strength of new concrete with lower w/c ratio (up to 0.42) results in higher compressive strength. (Mindess et al. 2003) But shear bond strength at the interface is affected by the material properties of both new and old concrete. Controversies still exist on how w/c ratio in new concrete affects shear bond strength. In order to find how the shear strength is affected by w/c ratio of the new concrete, two different w/c ratios (0.45 and 0.6) were chosen for the experiments.

Silica fume (7% by weight) was added as a SCM to study its effect on interfacial property. The addition of silica fume reduces the large pores and eliminates the growth of calcium hydroxide (CH).

3.2 *Specimen preparation*

Six sets of old concrete cubes with a size of 15cm (6 in.) were obtained from a previous study (See Fig. 1). For each test matrix a replica was made to find any outlier in making and testing specimens.

Figure 1. Overlaid Concrete Specimen.

A designated surface of all of the old cubes was swiped using sand paper to make the same surface texture. Air dry condition of old concrete was achieved by putting the old cubes in a laboratory keeping the relative humidity of 50% for several weeks. The SSD condition was made by putting the old concrete cubes in water for one day, removing the specimen from the water, and wiping out the moisture at the surface before placing on new concrete. Wooden forms were used to cast four specimens at the same time.

A typical concrete mixture used in Louisiana Department of Transportation and Development (DOTD) is used for new concrete (Table 2). Siliceous sand (TXI, Dennis Mills) and Kentucky limestone (limestone from three rivers rock quarry in Kentucky) were used for fine and coarse aggregates. Type I Portland cement was used. For all the mixtures, air entraining agents (Daravair 1400) were used. Normal water reducing agents were used for Mixtures A and C. A silica fume (micro-silica) with force 10,000 was added for Mixture C. The overlaid concrete specimens were moisture cured for 28 days before the shear bond tests. The compressive strengths of the overlay mixtures were measured at 28 days and are also shown in Table 2. Mixture A with a low w/c ratio (0.45) developed higher strength compared to Mixture B with low a w/c ratio (0.6). The Mixture C with a low w/c ratio (0.45) and 7% silica fume developed the highest compressive strength of the mixtures.

Table 2. Mixture Design and 28-day Compressive Strength.

Mixture	A	B	C
w/c ratio	0.45	0.6	0.45
Cement (lb)	475	475	475
Water (lb)	214	285	214
Limestone (%)	63.8	63.8	63.8
Sand (%)	36.2	36.2	36.2
Daravair 1400 (oz/100ct)	0.5	0.5	0.5
Additional (oz/100ct)	2.0 (WRDA35)	-	6.5 (AVDA370)
Silica Fume (%)	-	-	7.0
Compressive Strength (psi)	5,239	3,698	7,492

3.3 *Shear bond test*

After curing for 28 days, shear bond tests were performed on each specimen. A fabricated specimen was placed in loading frame as shown in Figure 2. Force was gradually applied until the specimen failed.

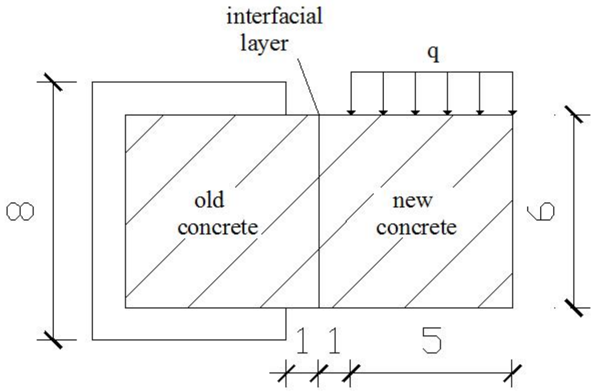

Figure 2. Shear bond test (unit: inches).

The overlaid concrete specimen cracked at the new concrete or deboned at the interface. The shear bond strenght is calculated from the measured failure force and surface area and provided in Table 3.

3.4 *Shear bond test results*

In Figure 3, the measured interface shear bond strength is compared to the compressive strength of new overlay concrete. In the figure solid symbol represents SSD condition, while the empty symbol is for air dry condition of old substrate. For the concrete without silica fume, the higher compressive strength (having lower w/c ratio) results in lower shear bond strength at the interface for both SSD and air-dry surface conditions. For the concrete with silica fume for 0.45 w/c ratio concrete, the compressive strength and shear bond strength were significantly increased. For all the tests, it was consistent that SSD surface condition resulted in higher (almost double) bond strength at the interface compared to air-dry condition. These test results imply that moisture condition at the interface in old concrete is very important to achieve high bond strength. Silica fumes in new concrete also contribute to increase shear bond strength at the interface.

Table 3. Results of Shear Bond Tests.

Mixture (w/c Ratio)	Silica Fume	Compressive Strength of New Concrete (lb)	Moisture Condition	Shear Bond Strength at Interface (psi)
A (0.45)	No	5239	SSD	269.8
			Air dry	150.8
B (0.6)	No	3698	SSD	485.1
			Air dry	263.9
C (0.45)	Yes	7492	SSD	767.9
			Air dry	518.8

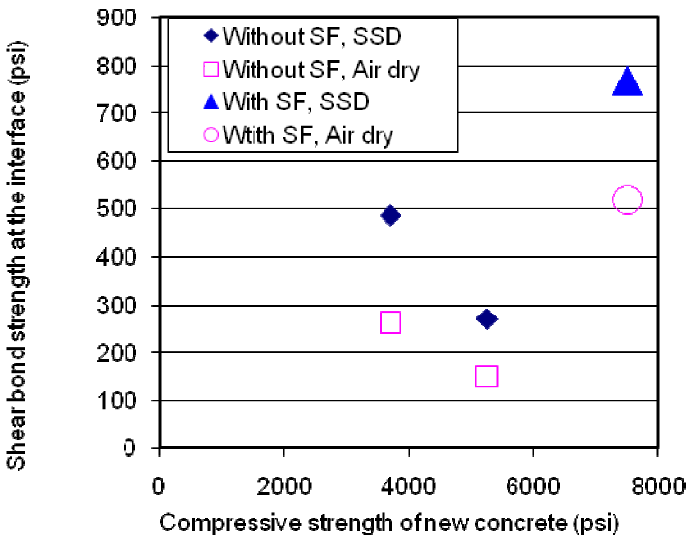

Figure 3. Shear bond strength vs compressive strength of new concrete.

3.5 *SEM analysis*

A Scanning Electron Microscope (SEM) was employed to identify the interfacial layer by analyzing crystal structure of Calcium Silicate Hydrate (C-S-H) and Calcium Hydroxide (CH) at the interfacial layer of new concrete. C-S-H is the most important hydration product and very strong and durable. The high surface area of C-S-H gives it a very strong strength. CH is a byproduct of hydration and weaker than C-S-H. It contributes little to strength.

A rectangular parallelepiped (1.5 in. x 1.5 in. x1 in.) was cut from the new concrete cube recovered at the shear bond tests in order to fit in the size of the container in SEM. The parallelepiped should contain the interface of the old concrete cube. Specimen surface was coated with Edwards S150 sputter coater to get high quality interface images as shown in Figure 4. Once the images were taken, the cement paste at the interface was further analyzed using EDAX attached in the SEM. The EDAX uses an X-ray source to quantify the elements of the selected area. Figure 5 shows the results of EDAX microanalysis report of the specimen shown in Figure 4. The average value of three EDAX analysis carried at different points on the surface were used for further analysis.

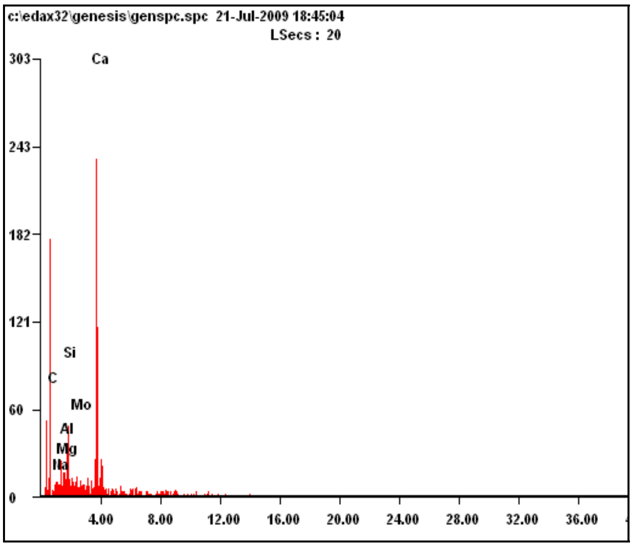

Figure 4. SEM image of the interface (Specimen #8).

KV:15.00 TILT: 0.00 TAKE-OFF:36.64 AMPT:102.4

DETECTOR TYPE :SUTW-SAPPHIRE RESOLUTION :131.99

Figure 5. EDAX Microanalysis Result (Specimen #8).

Two different methods were utilized to analyze the composition and microstructure properties at the interface. One was to estimate the composition of cement paste at the interface for different mixtures and moisture conditions, the other to find the composition trend of all the specimens from interface to 200 µm depth to identify interfacial zone.

The composition of cement paste at the interface was measured in a square area of 100µm. Since the majority of hardened cement paste is consisted of C-S-H and CH, the ratio of Ca/Si at the interface was used to correlate to the shear bond strength. Figure 6 shows a very strong relationship between the shear bond strength and Ca/Si ratio for the concrete mixtures without silica fume. With the increase of Ca/Si ratio, the shear bond strength at the interface increases linearly. The mixtures containing silica fume also have a similar trend. This high shear bond strength at the interface is considered due to pozzolanic reaction of silica fume with CH in the presence of moisture.

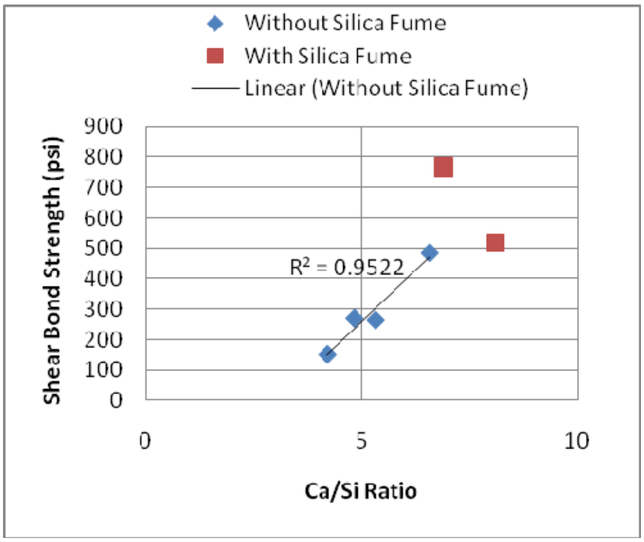

Figure 6. Relationship between shear bond strength vs. Ca/Si ratio.

To identify the interfacial zone at the interface, the composition of cement paste in new overlaid concrete was measured from the interface to a depth of 200 µm, and the Ca/Si ratio was calculated. The Ca/Si ratio increases with the depth for the mixtures not having silica fume, while the mixture with silica fume decreases with the depth. The interfacial zone is considered from the interface to the location where the peak of Ca/Si ratio reaches. The estimated interfacial zone is plotted against shear bond strength as shown in Figure 7. With the increase of interfacial zone, the shear bond strength decreases. This is related to low C-S-H contents at the interfacial zone, and consequently the shear bond strength is decreased for longer interfacial zone. Since the shear bond strength depends on the moisture condition of substrate and w/c ratio of the new concrete mixture, the interfacial zone would be changed with those conditions. These findings are very important to explain how the water in new overlay concrete and moisture in old overlaid surface affects the bond strength. This experimental study is very limited in sample size and test matrix, and further study with more extensive variable should confirm the observations.

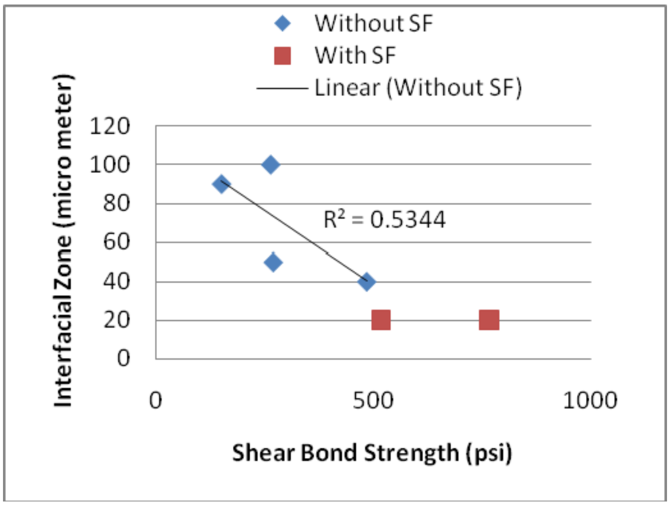

Figure 7. Shear bond strength vs. Interfacial zone of concrete mixtures.

3.6 *Ysis*

Rigaku MiniFlex XRD was utilized to investigate the material properties at the interface of new overlay concrete. The inside edge of new concrete interface was cut into a small piece (less than 0.5 mm or 0.2" thickness) to fit in the height of sample holder. The concrete piece was stick to the sample holder using play-doh to prevent any movement during the measurements. SCHV/PHA with 630 voltage was used to acquire x-ray for the measurement. The x-ray spectrum was analyzed using Jade5 software as shown in Figure 8. The analysis of the spectrum is progressing, and the analysis results will be compared with the shear bond strengths and SEM analysis results.

Table 4.Ternary Mixtures and Selected Mixtures for Bond Tests.

Mixture ID	Type I PC	Class C FA	Class F FA	G100 S	G120 S	SF
100TI	100%					
80TI-20C	80%	20%				
80TI-20F	80%		20%			
50TI-50G100S	50%			50%		
50TI-50G120S	50%				50%	
30TI-30G120S-40C	30%	40%			30%	
100TI-5SF	100%					5*

*5% silica fume addition

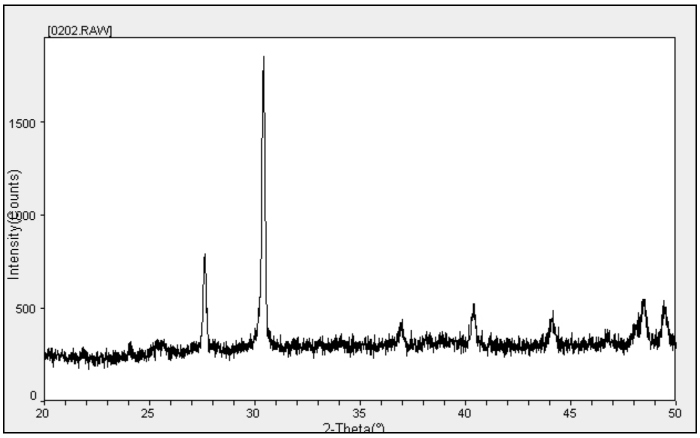

Figure 8. X-ray Spectrum of Specimen #2.

3.7 *Further study*

Currently a new experimental program is being progressed using seven mixtures. Six SCM replacements of new concrete mixtures, three different moisture conditions (wet, SSD after 1 day in water, and SSD after 3 days) of old concrete, and several w/c ratio of new concrete will be studied. As shown in Table 4, six mixtures with class C and F fly ash (FA), grade 100 and 120 ground granulated blast furnace slag, and silica fume (SF) were chosen to understand SCM effects on shear bond strength. After shear bond strength tests, SEM and X-ray Diffraction (XRD) analysis will be carried out to study the interface microstructure and moisture effects at the interface. This research will bring a better understanding of the interfacial properties and the effects of SCM in shear bond strength.

4 CONCLUSIONS

Based on the results presents herein, the following conclusions can be made:

- For the concrete without silica fume, higher compressive strength (having lower w/c ratio) results in lower shear bond strength at the interface for both SSD and air-dry surface conditions.
- By adding silica fume (7%) for 0.45 w/c ratio concrete, the compressive strength and shear bond strength at the interface increase significantly.
- SSD surface condition results in higher (almost double) bond strength at the interface compared to air-dry condition.
- There is a good relationship between the shear bond strength and Ca/Si ratio at the interface between new and old concrete. With an increase of Ca/Si ratio at the interface, the shear bond strength between two concretes increases. Since the Ca/Si ratio is an indirect measure of C-S-H and CH, the interface with high C-S-H contents results in high strength.
- The interfacial zone was identified from the Ca/Si ratio, and it has a good relationship with shear bond strength. As the interfacial zone is increased the shear bond strength decreased.

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