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Interfacial Properties between New and Old Concretes

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ABSTRACT

To better understand bonding mechanism at the interface between new and old 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 high w/c ratio. For all overlay concretes it was consistent that SSD surface condition results in much higher bond strength compared to air dry. SEM was employed to characterize material in micro-level at the interface and to determine interfacial zone.

INTRODUCTION

According to the 2009 Report Card by American Society of Civil Engineers, the average GPA of America's Infrastructure was graded as "D" due to a limited capacity and poor quality of old deteriorated infrastructure, and the total investment necessary for five-years was estimated as 2.2 trillion dollars. 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 behaviors at the interface between old construction material and new rehabilitation material, because 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 shorten service life. To better understand bonding mechanism at the interface between new and old concrete surfaces, it is essential to measure bond strength and the interfacial layer at the interface, and to investigate affecting parameters on the properties.

The interfacial layer between new and old concrete layers usually has different aggregate/cement contents, w/c ratio, and temperature evolution during the curing period compared to the other sides of new rehabilitation material and old construction material. The composition of the interface is affected by w/c ratio of rehabilitation material, surface moisture conditions, bonding agents, and other environment conditions. The interfacial layer is considered to have similar characteristics to the interfacial transition zone (ITZ) between

hydrated cement paste and aggregate. The ITZ between paste and aggregate is weaker 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 concentration of ettringite, and higher porosity. [Mindess et al.]

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 and 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.

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 new and old concrete layers.

RESEARCH SIGNIFICANCE

The infrastructures within the states of the US are suffering damages by increasing and unpredictable loads. To repair damaged infrastructure and enhance the structural capacity, 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 two materials. The findings of this research can be directly adapted in the rehabilitation of pavements and bridges.

EXPERIMENTAL STUDY

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 conditions were made on the old concrete surface to find how the bond strength is affected by the moisture condition of the old concrete.

The compressive strength of new concrete with lower w/c ratio (up to 0.42) results in higher compressive strength [Mindess et. al]. 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 ratio (0.45 and 0.6) were chosen for the experiments.

Silica fume (7% by weight) is 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).

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

Specimen Preparation

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

A designated surface of all 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 cube in a laboratory keeping the relative humidity of 50% for several weeks. The SSD condition was made by putting the old concrete cube in water for one day, removing the specimen from the water, and wiping out the moisture at the surface before placing 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 Table2. 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.

Shear Bond Test

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

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 </td <td>63.8</td>	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

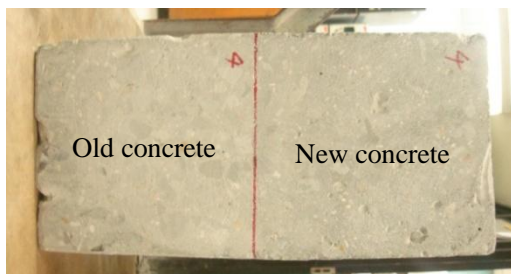


Fig. 1. Overlaid Concrete Specimen

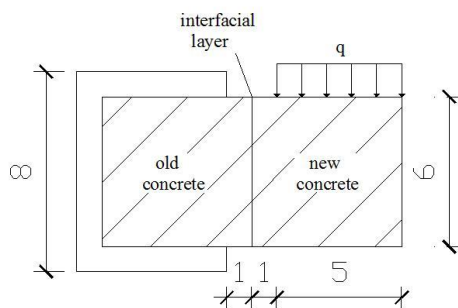


Fig. 2. Shear bond test

Shear Bond Test Results

In Figure 3, the measured interface 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. By adding silica fume for 0.45 w/c ratio concrete, we can significantly increase compressive strength and shear bond strength. For all the tests, it is consistent that SSD surface condition results 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 at the interface. Silica fumes in new concrete also 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	Average 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

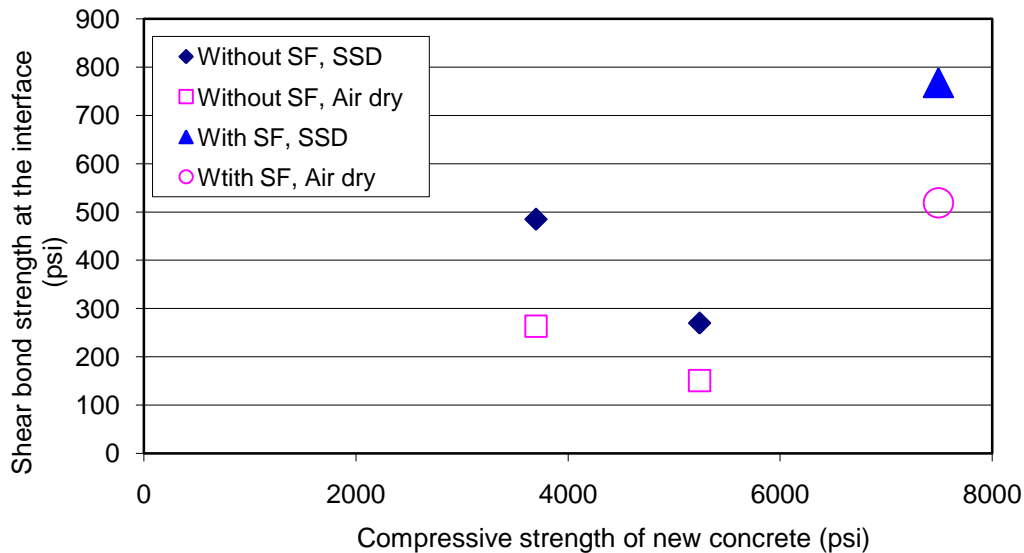


Fig. 3. Shear bond strength vs compressive strength of new concrete

SEM Analysis

HITACHI S-3600N 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) in 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. x 1 in.) was cut from the new concrete cube recovered at shear bond tests in order to fit in the size container in SEM. The parallelepiped should contain the interface of old concrete cube. Specimen surface were coated by Edwards S150 sputter coater to get high quality interface images as shown in Figure 4. Once the image was taken, the cement paste at the interface was further analyzed using EDAX attached in the SEM. The EDAX uses X-ray source to quantify the elements of the selected area. Figure 5 shows the results of EDAX microanalysis report. The average value of three EDAX analysis carried at different points on the surface were used for further analysis.

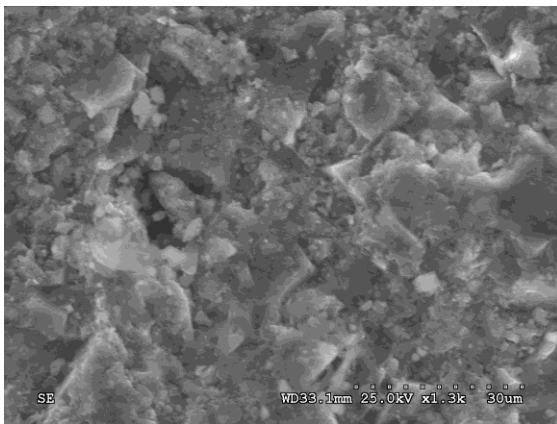


Fig. 4. SEM image of the interface (Specimen #8)

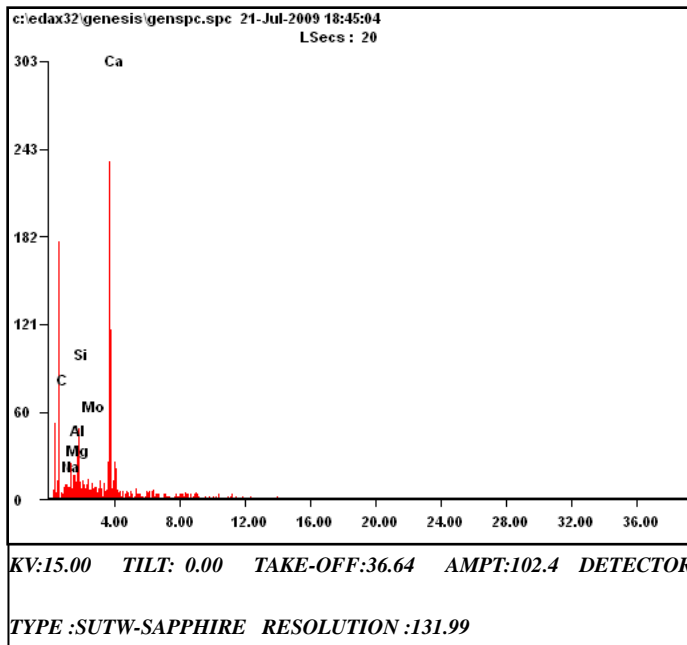


Fig. 5. EDAX Microanalysis Result (Specimen #8)

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 100 μm . 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. The mixtures containing silica fume also have a relative good relation. This high shear bond strength at the interface is considered due to pozzolanic reaction of silica fume with CH at the presence of moisture.

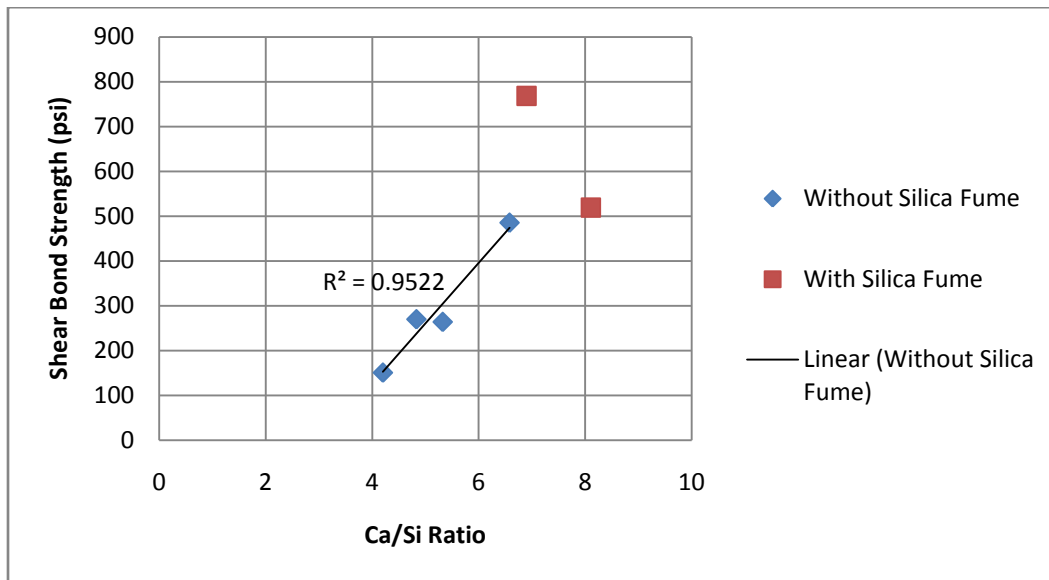


Fig. 6. Relationship between shear bond strength vs. Ca/Si ratio

To identify 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 is depend on the moisture condition of substrate and w/c ratio of new concrete mixture, the interfacial zone would be changed with those conditions. This finding is 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.

Currently a new experimental program is being progressed on using seven mixtures. Six SCM replacements of new concrete mixtures, three different moisture conditions (wet, SSD

after 1day 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 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 better understanding the interfacial properties and the effects of SCM in shear bond strength.

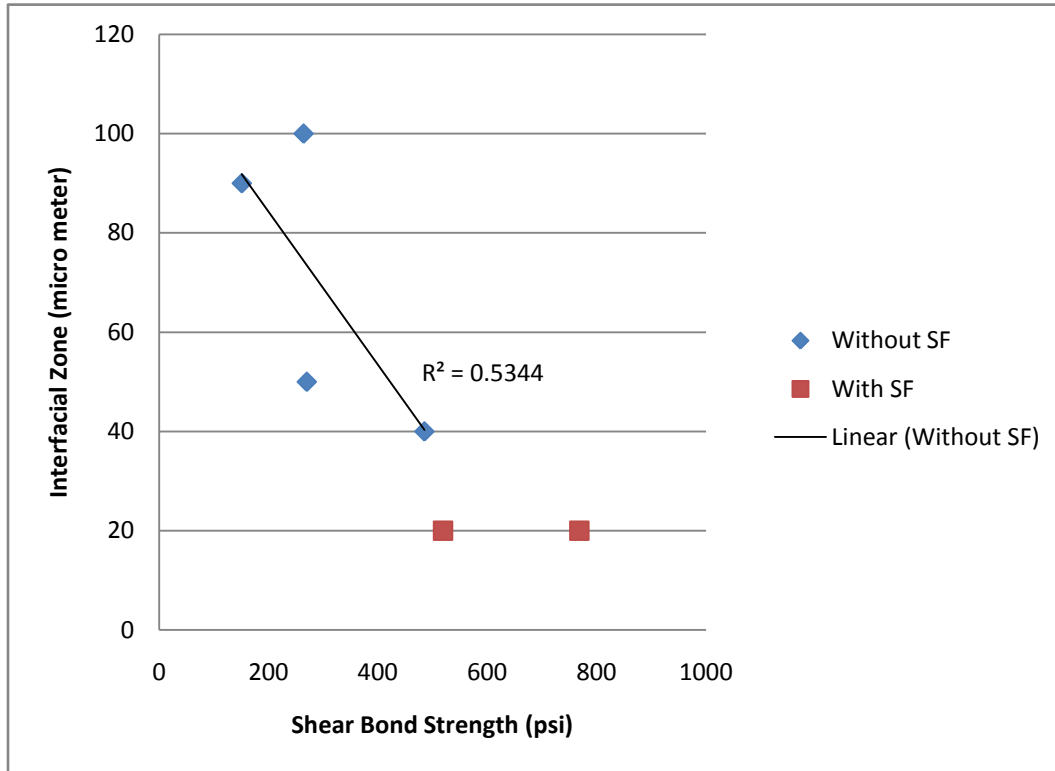


Fig. 7. Shear bond strength vs. Interfacial zone of concrete mixtures

Table 4. Ternary Mixtures and Selected Mixtures for Bond Tests

Mixture ID	Type I PC	Class C FA	Class F FA	G100S	G120S	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

CONCLUSIONS

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

- 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.
- 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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