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Mechanical properties of concrete to concrete interfaces under uniaxial and shear forces

Tek eksenli ve kayma yükleri etkisi altında beton-beton arayüzünün mekanik özellikleri

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Abstract

This research aims to evaluate the bond strength between normal strength substrate concrete and different types of high strength overlay concretes. In order to obtain different characteristics in the overlay concrete, silica fume and steel fibers were used. The slant shear and bi-surface shear tests were conducted to quantify the effect of different high strength concrete compositions on the bond strength. The mechanical properties of overlay/substrate concrete composites were also analysed on cylindrical samples under uniaxial compression load. The results indicate that the strength of overlay plays an important role on the bond mechanism. The bond strength is found to be dependent on the test mechanism. The test results showed that the bond strength was about 6-12 times higher in slant shear test compared to the bi-surface shear test. The application of parallel model approach on the overlay/substrate concrete composites was found to be quite satisfactory to predict the elastic modulus of the composite.

Keywords: Bond strength, Slant shear test, Bi-surface shear test

Öz

Bu deneysel çalışmada eski betonu temsilen normal dayanımlı beton ile yeni betonu temsil eden farklı tipteki yüksek dayanımlı betonlar arasındaki aderans dayanımının incelenmesi amaçlanmıştır. Farklı karakteristiğe sahip yeni beton elde etmek amacı ile silis dumanı ve çelik lif kullanılmıştır. Farklı kompozisyonlara sahip yüksek dayanımlı betonun aderans dayanımına etkisi eğik kayma (slant shear) ve çift yüzey kayma (bi-surface shear) deneyleri ile belirlenmiştir. Ayrıca eski/yeni beton kompozitlerin eksenel basınç yükü etkisindeki mekanik özellikleri deneysel olarak belirlenmiştir. Elde edilen sonuçlara göre yeni beton dayanımının ve kayma deneyinde kullanılan yöntemin aderans dayanımı üzerinde önemli bir etkisi olduğu görülmüştür. Eğik kayma deneyinin çift yüzey kayma deneyine göre 6-12 kat yüksek aderans dayanımı verdiği tespit edilmiştir. Paralel model yaklaşımının eski/yeni beton kompozitlerin elastisite modülünün tahmininde tatminkar sonuçlar verdiği belirlenmiştir.

Anahtar kelimeler: Yapışma dayanımı, Eğik kayma deneyi, Çift yüzey kayma deneyi

1 Introduction

Concrete structures, after many years in service, deteriorate due to several factors such as aggressive salts from the environment (i.e. chloride ion penetration, sulphate attack) and loads acting on the structures (i.e. service loads, earthquake loads). Depending on the extent of the degradation repair, strengthening or rebuilding of the existing structure should be considered. Repair and strengthening of concrete involves the removal of the existing concrete layer to ensure a strong bonding, followed by the application of an overlay which could be repair mortars or conventional concrete [1]-[3]. The success of rehabilitation and strengthening process of concrete structures relies on the quality of bonding between the concrete layers and therefore makes it important to assess the bond strength between old (substrate) and new (overlay) concrete [4],[5]. Many factors affect the bond mechanism of interfacial layer between the substrate and the overlay concrete. These factors generally include the compressive strength of the overlay and the substrate concrete, roughness of the substrate concrete surface, curing, and moisture condition of the substrate and the interface [6]-[9].

Bond strength between old and new concrete is a vital factor in repairing and strengthening applications and is still a hot topic in civil engineering [10]. Diab et al. [5] studied the parameters affecting the bonding mechanism between low strength conventional concrete and high strength self-compacting

concrete and found that compressive strength of overlay, surface roughness of the substrate concrete and additions to overlay concrete such as latex and fibers significantly affect the bond strength. Beushausen et al. [3] evaluated the effect of moisture level of substrate on the bond strength of substrate concrete/overlay concrete composites and found that prewetting the substrate prior to overlay concrete application had no benefit on the bond strength.

Julio et al. [10] investigated the effect of overlay compressive strength on the bond strength by slant shear test and found that the normal stresses at the interface increased with an increment in the difference between compressive strengths of overlay and substrate concrete and noted that overlay compressive strength might affect the bond strength. The current experimental work aims to research the effect of mechanical properties of substrate concrete and overlay concrete on the bond strength. To reach the aim, bond behaviour at the interface between substrate and overlay concrete is researched by slant shear test and bi-surface shear test. Moreover the mechanical behaviour of cylindrical composites composed of a normal strength substrate concrete covered with 4 different types of high strength overlay concretes (HSC) is also researched.

2 Experimental details

2.1 Materials and mix design

CEM I 42.5 R type of ordinary Portland cement (PC) complying with EN 197-1 [11] with specific gravity of 3.15 and Blaine fineness of 326 m^2/kg, was utilized for manufacturing substrate and overlay concretes. Silica fume (SF) was used as a mineral admixture in two of the overlay concrete mixes. The oxide content and the physical properties such as specific gravity and fineness of PC and SF are reported in Table 1. Siliceous sand and calcareous crushed stone sand (D_{max}=4 mm) were used as fine aggregates, and limestone aggregate (D_{max}=16 mm) was used as coarse aggregate in the concrete mixes. The particle density of coarse limestone, siliceous and crushed calcareous aggregates were 2.70, 2.56 and 2.68 kg/m^3 respectively.

Table 1: Oxide content (%) and physical properties of PC and SF.

Material	PC	SF
CaO	61.96	1.42
SiO_2	21.44	92.73
Al_2O_3	5.22	1.30
Fe_2O_3	3.26	0.28
MgO	1.16	0.75
SO_3	3.04	0.19
LOI	1.32	1.44
Specific gravity	3.14	2.32
Fineness (Blaine, m^2/kg)	365	21000

Polycarboxylic ether based chemical admixture with density of 1.10 g/cm^3 was used to obtain a slump value of 7±2 cm. The amount of superplasticizer was regulated at the time of mixing to obtain the specified slump.

A single type steel fiber was used for the production of fiber reinforced concretes. The properties of the steel fiber obtained from the manufacturer are presented in Table 2.

Table 2: Properties of steel fiber.

Shape	Diameter (μm)	Length (mm)	Tensile strength (MPa)	MOE (GPa)
Straight	150	13	3000	200

In this study, a total of 4 different high strength overlay concretes (NC, SFC, FRC and FRSFC) and 1 normal strength substrate concrete (SC) were prepared and coded as shown in Table 3. A concrete mixer with a vertical rotation axis was used for concrete production and the properties of concrete in fresh state were determined after complete the mixing and the results are presented in Table 4 along with the mix design.

2.1 Curing and testing procedure

In order to determine the mechanical properties such as modulus of elasticity (MOE), compressive strength and splitting tensile strength, all types of concretes were cast in standard Ø150/300 mm and Ø100/200 mm cylinder moulds, demoulded at 24h and kept in the storage room at 20±2 °C and relative humidity of 65±5% for 27 days. Compressive and splitting tensile strength tests were performed in agreement with EN 12390-3 [12] and ASTM C496 [13] respectively. Cylindrical specimens with dimensions of Ø150/300 mm were used to determine the static MOE as explained in ASTM C469 [14] using the stress–strain data, as given by Eq. (1).

$$E = \frac{(S_2 - S_1)}{(\varepsilon_2 - 0.00005)} \tag{1}$$

where E represents the MOE, S_1 is the stress corresponding to a longitudinal strain, ε_1, of 50 μm, S_2 is the stress corresponding to 40% of the maximum load and ε_2 is the strain produced by stress S_2. The longitudinal displacements was gauged with two linear variable differential transformers (LVDTs) on each specimen. For each mixture, the average value of the three specimens is reported here. The following steps were adopted to attain a proper stress–strain curve, [15]. The strain was considered to increase in 0.00001 mm/mm increments. The stresses corresponding to each strain data points were determined using the linear interpolation method.

Table 3: Definition of mixture codes.

Code	Definition
SC	Substrate concrete
NC	Plain HSC
SFC	SF added HSC
FRC	Fiber added HSC
FRSFC	SF and fiber added HSC
SC + NC	
SC + SFC	Composite samples composed of substrate concrete and different types of overlay concretes
SC + FRC	
SC + FRSFC	

Bond strength was determined by slant shear and bi-surface shear tests on cylindrical and cubic specimens respectively. The substrate concrete was initially placed into moulds, and a setting retarder was sprayed on the fresh concrete surfaces. The concretes were demoulded after 24 hours and the bond surfaces were roughened by using a stiff steel brush. The attention was paid to obtain similar roughness on the substrate surface to discard the effect of this parameter on the bond strength. The specimens were then kept under water for 5 days and air dried in the storage room for 24 h before the new concrete overlays were applied. The moisture condition of the substrate before casting the overlay concretes was dry. Prior to placing the overlays, the contact face of concretes was cleaned applying wire brush and high pressure air and the substrate concrete specimens were then returned to the moulds. Each empty part of the mould was filled with the overlay concretes. The overlay concretes were compacted with a steel bar and by tapping the mould sides with a plastic mallet.

The slant shear test was carried out as per ASTM C882/C882M-12 [16] on composite cylinders of 150 mm diameter and 300 mm height (Figure 1). In slant shear test, the overlay concrete is bonded to the substrate concrete on a slant elliptical plane inclined at an angle of 30° from the vertical axis (loading axis).

Figure 1: Specimens for slant shear test.

Table 4: Mixture design (kg/m³) and fresh state properties of concretes.

Mix code	Cement	Water	River sand	Crushed sand	Limestone coarse	Silica fume	Steel fiber	Super plasticizer	Slump (cm)	Fresh density
SC	230	161	490	719	829	--	--	2.3	5	2422
NC	350	157.5	468	686	791	--	--	4.6	6	2462
SFC	315	157.5	485	711	820	35	--	5.3	9	2459
FRC	350	157.5	464	681	786	--	39	7.0	5	2503
FRSFC	315	157.5	461	677	780	35	39	7.7	7	2501

The bi-surface shear test was carried out on 150 mm cubic specimens where the substrate concrete layer and the overlay concrete layer account for two-thirds and one third of the volume of the specimen (Figure 2), respectively. The composite specimens are tested under compression using three steel plates, with 50x150x25 mm³, originating two shear planes where one shear plane corresponds to the bonded interface, and the second plane is located in the substrate concrete. The specimen shape and proportions are illustrated in Figure 3 for slant shear and bi-surface shear tests.

Figure 2: Specimens for bi-surface shear test.

The behaviour of composite specimens under uniaxial loading was also researched by covering a specific volume of substrate concrete by the overlay concrete as shown in Figure 4 and Figure 5. Initially, substrate samples were cast in 75x300 mm (diameter x height) cylinder moulds. Samples were demoulded 24 hours after casting and the lateral surfaces of the samples were roughened the same way as in the shear test samples. The test specimens were then immersed in water for 5 days and kept in the storage room for 1 day.
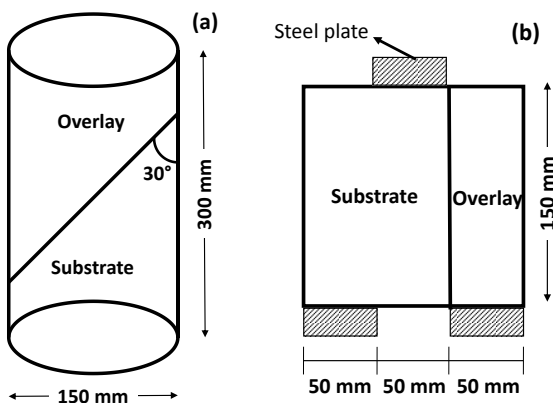

Figure 3: Specimen geometry and dimensions for.
(a): Slant shear, (b): Bi-surface shear.

The substrate cylinders of Ø75/300 mm were placed in the middle of standard Ø150/300 mm moulds and the overlay concrete was cast around it. The composite samples were demoulded after 24h and cured in the storage room for another 27 days.
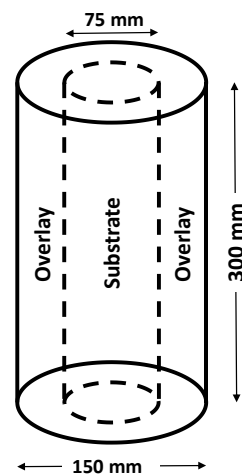

Figure 4: Scheme of composite specimen composed of substrate and overlay.

Figure 5: Composite specimens tested under uniaxial loading.

3 Results and discussion

3.1 Mechanical properties of concrete mixes

Table 5 presents the average compressive strength, MOE and splitting tensile strength values of concrete series. Compressive strength of the substrate concrete was, as expected, the lowest as 39 MPa. The overlay concretes had higher strength values compared to that of the substrate concrete and the strength values varied between 60.8 and 76.9 MPa. The addition of SF, steel fiber, and SF and fiber together resulted in higher

compressive strength as shown in Table 5. The MOE of concrete mixes followed a similar fashion as in compressive strength and varied between 34813 MPa and 42355 MPa. Splitting tensile strength of the substrate concrete was 3.64 MPa and varied between 4.69 and 6.14 MPa for the overlay concretes. The inclusion of steel fiber improved the tensile strength by 17% and the addition of SF and fiber together resulted in an enhancement of 31% compared to NC mix. The partial utilization of SF by cement resulted in denser and improved microstructure which affected the strength characteristics of concrete as clearly seen in Table 5.

Table 5: Mechanical properties of concrete series.

Concrete Layer	Mix code	Compressive strength (MPa)	MOE (MPa)	Splitting tensile strength (MPa)
Substrate	SC	39.0	34813	3.64
Overlay	NC	60.8	38276	4.69
	SFC	70.3	42355	4.78
	FRC	62.6	35748	5.48
	FRSFC	76.9	39490	6.14

3.2 Mechanical properties of composites composed of substrate and overlay concretes

Figure 6-9 shows the compressive strength, MOE and the stress-strain curves of concrete mixes and the composites (cylindrical samples composed of overlay and substrate concretes) respectively. It is clear from the Figure 6 that the compressive strength of composite mixes possessed higher strength values than the substrate concrete but failed to reach or exceed the strength of overlay concretes. A similar trend was also noticed on the MOE of composite mixes, plotted in Figure 7. Based on the compression test result carried out on both plain and composite test specimens. It was observed that the strength loss generally increased with an increase in overlay concrete which verifies the influence of the rigidity difference of concrete layers. The highest strength loss was noticed in SC+FRSFC composite mix as 26% while the lowest loss was observed in SC+NC composites as 9% compared to FRSFC and NC mixes respectively.

The usage of steel fibers resulted in an increment of strain corresponding to the peak stress (Figure 7). Especially the FRSFC has remarkably higher strain capacity than other mixes. However, the remarkable effect of fiber addition on the stress-strain behaviour of composites was noticed in the FRC confined composites. The results show that stress-strain behaviour of substrate concrete has changed significantly when confined with new concrete (Figure 8). The FRC confined SC composite is more ductile than both SC and FRC when subjected to uniaxial stress. The significant effect of FRC can be seen obviously in the post peak, descending part of the curve. The toughness of the SC+FRC composite, the area under the stress-strain curve, is greater than other composite series. In any cases debonding or shear failure was not observed. The failure can be characterized as vertical cracks and it can be said that the ultimate strength of overlay concrete was major parameter that governs the compressive strength of composite.
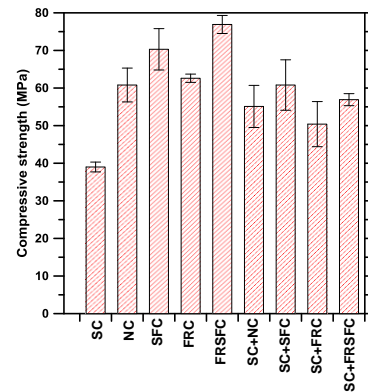

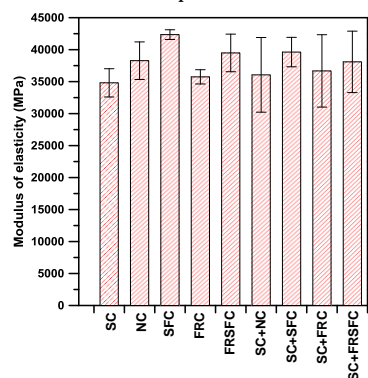Figure 6: Compressive strength of concrete mixes and composites.

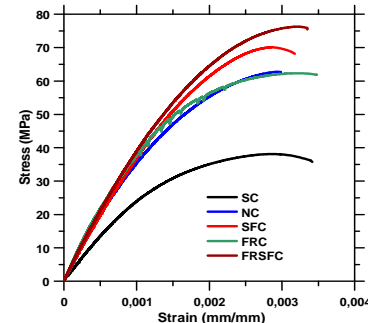Figure 7: MOE of concrete mixes and the composites.

Figure 8: Stress-strain curves of concrete mixes under uniaxial loading.
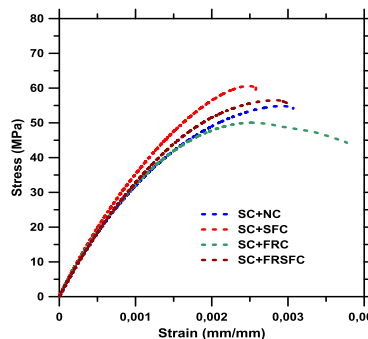

Figure 9: Stress-strain curves of composites under uniaxial loading.

Application of parallel model (Eq. (2)) approach [17] was found to be quite satisfactory to estimate the MOE of composite concrete members (Figure 10).
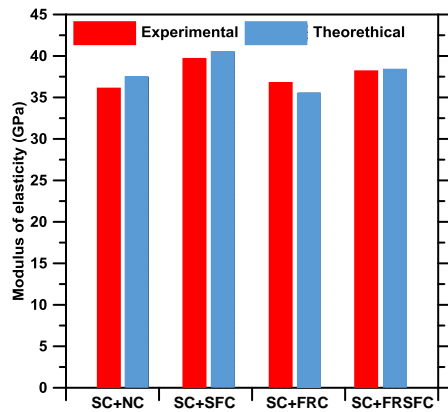
Figure 10: Experimental and theoretical results of MOE of composites.

The composite concrete was assumed to be composed of two phases (substrate and overlay concrete), where the volume of substrate concrete corresponds to 25% and the volume of overlay concrete corresponds to 75% of the total composite volume.

$$E_c = E_1 V_1 + E_2 V_2 \qquad (2)$$

In Eq. (2), E_c, E_1 and E_2 are the MOE of composite, substrate concrete and overlay concrete, respectively; and V_1 and V_2 are the volume fractions of substrate and overlay concrete.

3.3 Shear test

Shear test results are depicted in Figure 11. The results indicate that the increase in the overlay concrete strength also improved the bond strength of concretes, similar results are reported by other researchers [3],[5],[10],[18]. Although SF incorporation was dramatically increased the bond strength calculated from in bi-surface shear test, the same performance of SF was not notable when the slant shear test results were considered. However, the highest improvement in the bond strength was observed on SC+FRSFC samples where SF and steel fibers were introduced in the overlay concrete. The effect of overlay concrete properties on the bond strength was more clearly noticed in the bi-surface shear test; as the overlay concrete compressive strength increased the shear strength increased up to about 2 times the SC+NC mix. The bi-surface shear strength varied between a broader ranges of 1.3-2.9 MPa compared to the slant shear strength. The slant shear strength was found to be between a narrow ranges of 15.8-16.8 MPa, but an increasing trend with an increment in the overlay compressive strength can be noticed in Figure 12.
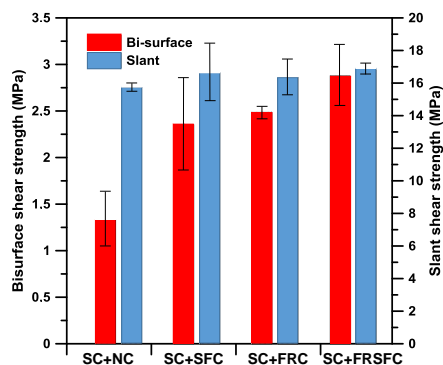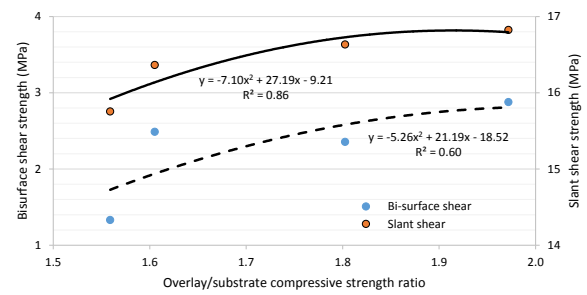

Figure 11: Shear test results.

Figure 12: The relation between bond strength and overlay/substrate compressive strength ratio.

Test results also reveal that the value of bond strength depends on the test method. The slant shear test results were found to be 6 to 12 times higher than the bi-surface shear test results. As explained by Momazey et al. [4], higher compressive stresses occur in slant shear test which develop extra friction forces between the substrate and overlay interface which consequently increase the ultimate shear load.

The specimens were visually observed in detail to identify the crack formations and failure modes after the shear tests. Three failure modes were identified as shown in Table 6. The concrete specimens failed due to the

i.   Interface failure (IF),
ii. Interface+substrate failure (ISF), and
iii. Mixed failure (combined failure of interface, substrate and overlay).

Table 6: Failure modes of concrete mixes after shear test.

Mix code	Sample #	Failure Mode	
		Bi-shear	Slant shear
SC/NC	1	IF	Mixed
	2	IF	Mixed
	3	IF	Mixed
SC/SFC	1	ISF	IF
	2	IF	IF
	3	IF	IF
SC/FRC	1	IF	IF
	2	ISF	IF
	3	IF	IF
SC/FRSFC	1	IF	IF
	2	IF	IF
	3	IF	IF

The most governing failure mode in bi-shear test was the interface failure (Figure 13a). On the other hand, in some samples of SC+SFC and SC+FRC mixes, the failure occurred both at the interface and at the substrate as shown in Figure 13b (Note that the cracks are highlighted).
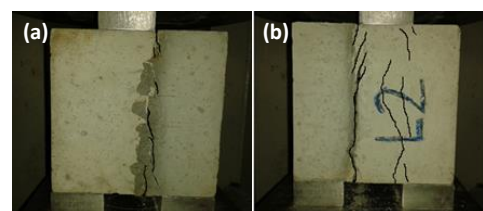

Figure 13: Failure modes in bi-shear test. (a): Interface failure, (b): Interface + substrate failure.

In slant shear test two distinctive failure modes were seen; interface failure (Figure 14a) and mixed failure (Figure 14b).
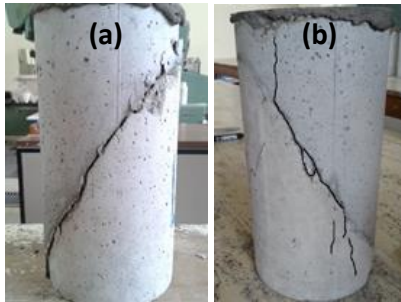

Figure 14: Failure modes in slant shear test. (a): Interface failure, (b): Mixed failure.

4 Conclusions

This research experimentally investigates the bond strength between normal strength substrate concrete and different types of high strength overlay concretes by two different shear test methods. Mechanical properties of composite concretes composed of overlay and substrate concretes were also analysed on cylindrical samples under uniaxial compression load. According to the test results, the conclusions are summarized as follows:

- Test results on the composites revealed that the compressive strength and MOE of composite mixes possessed higher values than the substrate concrete but failed to reach or exceed the overlay concretes. The application of parallel model approach was found to be quite satisfactory to estimate the MOE of composite concretes,

- The increase in the overlay concrete strength improved the bond strength of concretes. The highest improvement in the bond strength was observed on SC+FRSFC samples where SF and steel fiber were introduced together in the overlay concrete,

- The effect of overlay concrete properties on the bond strength was more clearly noticed in the bi-surface shear test, as the overlay concrete compressive strength raised the shear strength about 2 times compared to the SC+NC mix.,

- The slant shear strength was found to be between a narrow ranges of 15.8-16.8 MPa, but followed a rising trend with an increment in the overlay compressive strength,

- The bond strength value is found to be highly dependent on the test method. The slant shear test results were about 6-12 times higher than the bi-surface shear test results,

- The most governing failure mode in bi-shear test was the interface failure (bond failure). On the other hand, in slant shear test two distinctive failure modes were observed; interface failure and mixed failure.

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