

An Experimental Study on the Bond Strength of Old and New Cementitious Materials

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ABSTRACT

Due to climate change in most countries, construction tends to take less time than planned. Therefore, prompt repairs are needed to extend service life. One repair method is pouring new concrete onto the old, particularly for concrete pavement. However, the bond between them presents a significant challenge. This paper presents an experimental study on the bond strength of new and old concrete. The pull-off or direct tensile test was conducted to address this issue. Three substrate treatments were used: as-cast, connecting-hole, and steel brushing. The experimental results indicated that the bond strength between the old and new concrete in the as-cast substrate treatment was the lowest. In contrast, the connecting-hole and steel brushing treatments resulted in strengths that were 19% and 45% higher, respectively, than the as-cast treatment. The bond strength for the connecting-hole treatment was less than that of the steel brushing treatment, possibly due to the unsuitable hole size. The failure mode observed in this test was substrate fracture rather than sharp debonding of the two layers. That is, delamination between the old and new concrete layers did not occur. This confirms the feasibility of the repair method considered in this study for the old concrete pavement in the future.

Keywords-bond strength; cementitious material; pull-off test; glass fiber-reinforced self-compacting mortar; manufactured sand

I. INTRODUCTION

Cementitious materials, especially concrete, are widely used in engineering due to their versatile properties. Concrete is a mixture of cement, aggregates, water, and sometimes mineral or chemical admixtures. In its fresh state, it is plastic and workable, which allows it to be easily shaped. Its strength develops through hydration, a chemical reaction between cement and water that produces calcium silicate, calcium aluminates, and calcium hydroxide. These compounds form a solid matrix that binds the aggregates and gives the concrete its durability. Concrete is much stronger in compression than in tension, which is why it is typically used in compressive load applications, such as gravity dams and foundations, known as plain concrete [1]. To resist tensile stresses, steel reinforcement bars are embedded in the concrete. However, steel alone may not adequately resist shear and impact forces. As a result, various fibers—including steel, polypropylene, glass, and natural fibers—are added to improve toughness and tensile strength [2, 3]. Concrete pavements have long been used for transportation infrastructure in countries like Vietnam [4]. When subjected to loads, stresses develop in the pavement. Initially, these stresses are managed within the elastic range of the material. However, due to its high stiffness relative to the

underlying foundation, the pavement bends under load. If it is too thin, it will deform and crack once the tensile strength is exceeded. Cracks typically begin as a single surface crack and worsen as stress increases, eventually leading to significant damage [5]. Beyond the elastic stage, transverse cracks appear at regular intervals, while longitudinal cracks often form along the centerline of the pavement embankment [5]. The pavements are often subject to periodic expansion and contraction due to changes in temperature and humidity. Unsealed joints are filled with loose granular materials, which will then hinder panel expansion when exposed to high temperatures. If this process continues for a long time, it will cause the following phenomena [6]:

- Stress concentration at cracks can lead to severe edge breakage of the concrete panels.
- In long roadway stretches, increased compressive forces generate horizontal stresses within the structure, resulting in significant damage.
- Continuous vehicle traffic causes fatigue in the concrete, reducing its tensile flexural strength and shortening its service life, eventually leading to failure.

- Water can easily infiltrate through cracks and joints between the foundation and the ground, weakening both and causing poor bonding between the slab and the foundation—this is known as the “slab channeling” phenomenon.
- Concrete damage can also result from improper mixed composition or failure to meet the required design strength. Additionally, insufficient moisture during early curing stages and poor maintenance during use accelerate deterioration. If small, damaged areas are not repaired promptly, they can rapidly grow and become more severe over time.

As soon as the crack propagation occurs on the concrete pavement surface, it needs to be repaired promptly to prevent the consequent failure. One of the preventive measures is to place fresh concrete onto the damaged concrete surface to have a new layer covering the old one [7]. However, the bond between the old and newly cast concrete is the most important key, because if delamination between the layers occurs, this approach will not work out. Therefore, this paper aims to present an experimental study on the bond strength of the new and old concrete. The experimental test results verify whether there is a delamination between the new and old concrete layers. This would confirm the feasibility of the aforementioned preventive method.

II. MATERIALS AND METHODS

A. Materials Used for the Experiment

In this study, Ordinary Portland Cement PC40 Type I, complying with the European cement standard [8], was utilized. The specific and bulk densities of cement are 3.11 g/cm^3 and 1.33 g/cm^3 , respectively. Its Blaine fineness and consistency are $3430 \text{ cm}^2/\text{g}$ and 28.5% , respectively. Additionally, the initial setting time, final setting time, and soundness of cement are 160 min, 240 min, and 1 mm, respectively. Finally, its compressive strength at 3 and 28 days is 24.1 MPa and 45.5 MPa, respectively. Elkem Microsilica@ 940, a silica fume complying with [9], was utilized in conjunction with the cement as an additional cementitious material. Table I provides the physical and chemical properties of the silica fume.

TABLE I. PHYSICAL AND CHEMICAL CHARACTERISTICS OF SILICA FUME

Parameters	Units	Test results
Specific density	g/cm^3	2.1
Bulk density	g/cm^3	0.93
Loss on ignition	%	4.2
Content of SiO_2	%	93.5
Content of Al_2O_3	%	0.92
Content of Fe_2O_3	%	0.52
Content of SO_3	%	0.63
Content of CaO	%	1.57

As proposed in [10], crushed-stone sand is used in this study as a cost-effective alternative to natural river sand, with its properties being detailed in Table II. To assess the grading of the aggregates, a sieve analysis was also conducted, with the results being provided in Table III. Alkali-resistant glass fiber, compliant with the specifications in [11], is incorporated into

the mix, and its properties are shown in Table IV. A third-generation polycarboxylate-based superplasticizer, known for its high-range water-reducing capabilities, is used to enhance the mixture's workability. Tap water is also utilized in the mix design. The characteristics of both the superplasticizer and the water are presented in Table V.

TABLE II. CHARACTERISTIC OF CRUSHED-STONE SAND

Parameters	Units	Test results
Specific density	g/cm^3	2.67
Bulk density	g/cm^3	1.65
Porosity	%	38.2
Moisture content	%	1.0
Clay, silt, and dust content	%	0.5
Fineness modulus	-	2.57

TABLE III. GRADATION OF MANUFACTURED SAND BY SIEVE ANALYSIS

Sieve size (mm)	Crushed-stone sand
5	0
2.5	9.0
1.25	23.5
0.63	46.3
0.315	84.0
0.14	95.5
Pan	100

TABLE IV. CHARACTERISTICS OF GLASS FIBER

Glass fiber	Units	Value
Length	Mm	17
Content of ZrO_2	%	18.5
Specific density	g/cm^3	2.5
Tensile strength	MPa	1600

TABLE V. CHARACTERISTICS OF SUPERPLASTICIZER AND WATER

Parameter	Units	Superplasticizer	Water
Specific density	g/cm^3	1.075/1.095	1
pH value	-	4/6	7

B. Old and New Concrete

The old concrete used was a beam-type specimen that had been produced one year prior to testing. At the time of the experiment, it exhibited a compressive strength of 25 MPa and was treated as the substrate material. The new concrete was prepared with the inclusion of glass fibers, designed to achieve a compressive strength of 50 MPa at 28 days. In its fresh state, the mixture was sufficiently workable to eliminate the need for mechanical compaction, behaving similarly to a Self-Compacting Mortar (SCM). The mix design was based on the recommendations for Self-Compacting Concrete (SCC), originally developed by Okamura [12], who is recognized as the pioneer in introducing SCC to the scientific community. This approach was chosen due to the lack of specific standards or guidelines for SCM incorporating glass fiber. Additionally, several SCC guidelines published by EFNARC were taken into consideration [13, 14]. Detailed procedures for mix design were found in [15]. To achieve a slump flow of 20 cm, in accordance with the requirements outlined in [16], a trial-and-error approach was employed. The final SCM mix proportions used in this investigation are presented in Table VI.

TABLE VI. MIX PROPORTION OF SCM STRENGTH CLASS 60 MPA

Cement	Silica fume	Sand	Super-plasticizer	Water	Glass fiber
kg	kg	kg	l	l	%
400	40	1715	5.1	196	0.1

C. Preparation of the Interlayer Surface

Given that the bonding behavior is crucial for repairing the old concrete pavement, the old concrete surface treatment also plays an important role. In this study, three types of surface treatment for the old concrete are examined. The first one involves using the steel brush to remove the cavities on the old concrete surface, as seen in Figure 1. This would yield a smooth surface before placing the new, fresh glass fiber-reinforced SCM.

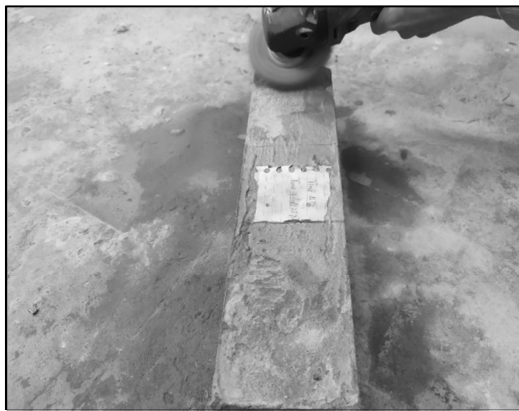


Fig. 1. Steel brush treatment.

The second surface treatment involves drilling a series of small connecting holes into the old concrete, as illustrated in Figure 2. These holes act as mechanical connectors between the old and new concrete layers, helping them interlock and form a stronger bond. Each hole is 3 mm deep and 5 mm in diameter, created using an electric drill. The third treatment, referred to as the "as-cast" surface, involves no mechanical alteration. The surface is simply cleaned to remove loose particles before the fresh SCM is applied. Figure 3 also shows the specimen prepared with this as-cast treatment. After treating the old concrete surface and preparing the SCM, the new mortar is poured into a steel mold containing the old concrete beam at the base. The casting process is complete when the mold is fully filled with fresh SCM. The specimen is then left in the mold for 24 hours. It has dimensions of 100 mm × 100 mm × 400 mm. Following demolding, the specimen is cured under standard conditions (temperature: 20°C–25°C, humidity: >90%) for the first 72 hours. After that, curing continues under laboratory conditions (temperature: 25°C–30°C, humidity: 65%–90%).

D. Bond Strength Measurement

Bond strength was determined by the digital pull-off strength tester Matest® E142 [17], as can be seen in Figure 4. This dynamometer is useful for applications involving the testing and repair of any structure, where the bond strength between two layers is significant. It measures the adhesive

force and the tensile strength of two layers of materials (concrete, facing plasters, mortars, building plasters, lime, etc.). This pull-off tester is lightweight, portable, and equipped with a load cell and a large digital display unit with high resolution. As a result, it can measure loads as low as 16 kN, providing a broad working range and making it perfect for a variety of materials and applications. The hand wheel is rotated to apply the direct tensile tension. To conduct experiments in confined places or for specimens that are near one another, the unit's three feet can be fixed in either the compact position (overall dimensions 92.5mm diameter) or the large position (overall dimensions 176 mm diameter) with extremely stable bearings. This pull-off or direct tensile test measures the specimen's tensile stress by applying a perpendicular force to the bonding surface. The tensile test procedure is carried out in a way that minimizes the specimen's susceptibility to eccentricity [18].



Fig. 2. Connecting hole treatment.

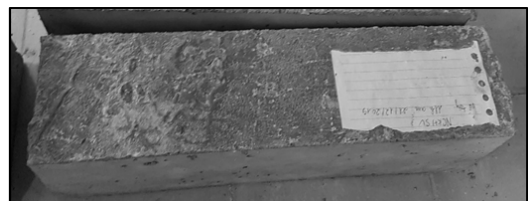


Fig. 3. As-cast treatment.

III. RESULTS AND DISCUSSION

A. Bond Strength from Different Substrate Treatments

Figure 5 presents the bond strength results for the three different substrate treatments: as-cast, connecting-hole, and steel brushing. Among them, the as-cast surface exhibited the lowest bond strength. In comparison, the connecting-hole and steel brush treatments produced bond strengths that were 19% and 45% higher, respectively. The steel brush treatment resulted in the highest bond strength, which may be attributed to two factors. First, brushing the surface creates a smoother and more uniform substrate. Second, the new concrete used in

this study is a high-strength SCM containing fine particles that help reduce the effects of cold joints between the old and new concrete layers, thereby enhancing the bond. Although the connecting-hole treatment involved creating mechanical connectors between the layers, its bond strength was still lower than that of the steel brush treatment. This may be due to size of the holes being suboptimal, which likely prevented the fresh SCM from fully penetrating and forming a strong interlock during casting. Overall, the bond strength trends observed in this study are consistent with findings reported in [19–25].



Fig. 4. Equipment used for the direct tensile test.

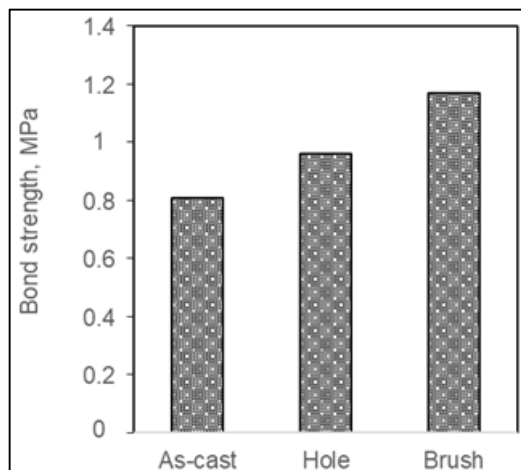


Fig. 5. Bond strength from different substrate treatments.

B. Interlayer between the Old and New Materials

The typical failure mode from the pull-off or direct tensile test is shown in Figure 6. The test specimens are created by

drilling a cylindrical core that has a diameter of 50 mm and a height of 15 mm beneath the substrate layer interface in concrete samples. To apply tensile tension, a steel disc is then adhered to the upper surface of the core [19]. Instead of a sudden debonding of the two layers, substrate fracture is the failure mode observed in this test. This means that delamination between the old and new concrete layers did not occur, confirming the effectiveness of the proposed repair method for the old concrete pavement.

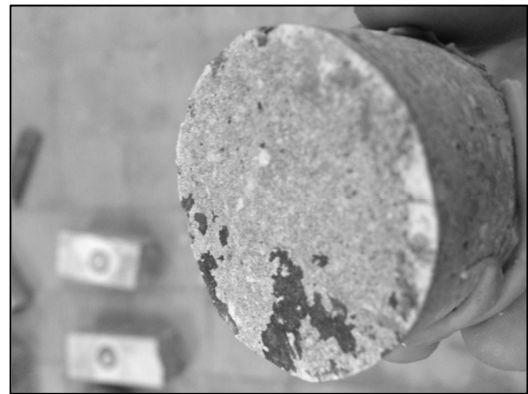


Fig. 6. Typical failure mode from the direct tensile test.

IV. CONCLUSIONS

This study investigated the bond strength between old and new cementitious materials, focusing on applications in civil engineering and concrete repair. The bond performance was evaluated using the pull-off (direct tensile) test. Three types of substrate surface treatments were examined: as-cast, connecting-hole, and steel brushing. The results showed that the as-cast surface produced the lowest bond strength. In contrast, the connecting-hole and steel brushing treatments improved bond strength by 19% and 45%, respectively, compared to the as-cast condition. The highest bond strength was achieved with the steel brushing treatment. This can be attributed to two key factors: the improved surface roughness created by brushing and the use of high-strength Self-Compacting Mortar (SCM). The latter contains fine particles that enhance interfacial bonding by reducing the potential for cold joints between the old and new concrete. Although the connecting-hole method introduced mechanical interlocking, its bond strength remained lower than that of the steel brushing method, possibly due to limitations in hole geometry or effectiveness. The failure observed in all tests was a substrate fracture, rather than delamination at the interface, indicating a strong bond between the old and new concrete layers. These findings support the efficiency of this repair technique for extending the service life of existing concrete pavements.

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