Effects of Concrete Substrate Condition on Fiber-Reinforced Composite Strength Properties

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ABSTRACT

This study determined the effects of concrete substrate conditions on the strength properties of fiber-reinforced composites through experimental research. The method of concrete surface preparation and moisture conditions were considered crucial parameters that have a significant impact on Fiber-Reinforced Composite (FRC) strength properties. Four different concrete surfaces were examined: grinded (CSP 2), sanded (CSP 3), scabbed (CSP 8), and unprepared (CSP 1), all under various moisture conditions: dry concrete substrate, saturated surface dry concrete substrate, and wet concrete substrate. A mix design conforming to the C25 grade concrete was formulated, cured in water for 7 and 28 days to achieve the desired design strength values. The dry surface specimens were cured in the air for at least 24 hr before subsequent preparations, the wet surface specimens were cured in water for at least 24 hr, while the saturated surface dry specimens were cured in water for 24 hours and then removed from the water and cured in the air for 1 hr. The prepared samples were carbon-wrapped with unidirectional SikaWrap-300 C and Sikadur 300 resin and then subjected to a uniaxial compressive strength test until failure after 24 hr of curing using a load of 0.2 MPa/sec. The collected data showed that the surface roughness of the CSP 8 under wet moisture conditions exhibited the best bond strength due to the increase in surface area for adhesive bond contact, while the wet substrate condition increased hydration on the adhesive side of the interface, which directly contributed to the increase in bond strength. All substrate conditions demonstrated cohesive cracking of the concrete substrate leading to displacement of the FRP-concrete interface before FRP rapture.

Keywords-FRP composite materials; concrete substrate; concrete surface profiles

I. INTRODUCTION

The construction industry is an important part of the economy of Kenya and one of the drivers of economic growth. It is part of the major pillars of Vision 2030 that seeks to increase the country's gross domestic product and propel Kenya towards becoming Africa's industrial hub. The Kenyan construction industry has been under immense pressure not only to provide affordable housing and related infrastructure facilities under the Kenya Big Four Agenda but also to guarantee a safe built environment. In the last three decades, the construction sector in the country has been characterized by unsafe buildings that are dangerous for human habitation. Building failure is one of the dominant challenges facing the industry in Kenya, as more than 100 cases of building collapse have been recorded since 1990. Structural failure in buildings at the time of construction or after completion can cause human casualties, wasted money, social disturbance, clashes, and claims between stakeholders [1]. An audit carried out in 2018 by the National Buildings Inspectorate (NBI) covering 14,925 buildings revealed that 723 (4.8%) were very dangerous, 10,791 (72.3%) were unsafe, 1217 (8.25%) were fair, and 2194 (14.7%) were safe. It is estimated that over 200 people have lost their lives since 1990 in building collapses, with thousands injured. The economy has also lost more than Kshs 2.4 billion worth of investments. Additionally, according to research conducted in 2020 by the National Construction Authority, of 87 documented cases of building collapses, 66% of the buildings collapsed during the utilization stage, while 34% collapsed while still under construction. Evaluation of existing reinforced concrete structures has become a necessary and important process for engineers on a large scale due to the aging of existing structures and buildings, as reinforced concrete has become a global construction material during the last decades [2]. Structural evaluation and past research in the Kenyan construction industry have revealed that a large number of existing facilities need maintenance, retrofitting, rehabilitation, and restoration as a result of natural or man-made factors and causes such as natural disasters, earthquakes, wars, conflicts, and other sudden causes that lead to various degrees of damage. The 2015 National Building Maintenance Policy recommends a periodic five-year inspection of all categories of buildings, while there should be a critical inspection of buildings aged 30 years and older to detect signs of failure.

The recent change in economic balance from removal-replacement toward building rehabilitation has been rapid and inevitable in Kenya. Therefore, the most economical and effective techniques for structural rehabilitation are needed. Structural rehabilitation represents a very essential aspect of the construction industry, and its importance is increasing. There are numerous methods available, each with different benefits and shortcomings. Traditional methods of repairing and strengthening concrete structures can be widening the cross-section, using external pre-stressing or steel plate bonding, concrete jacketing, demolition and recasting afresh, etc. However, the cost of strengthening and maintenance repairs with these traditional materials and their vulnerability to environmental effects, leading to corrosion and shorter life spans, motivated engineers to look for alternative materials and methods. In addition, these methods involve bulky work and do not offer simple and quick solutions to the rehabilitation of structures. As a result, there is a rapid shift to superior modern methods of structural rehabilitation around the world, especially in developed countries, due to the growing need for faster and more economical retrofitting techniques due to the ever-aging infrastructure and damage caused by major catastrophic events [3]. FRP composites represent the latest advances in this regard, as they have superior durability and versatility compared to traditional construction materials. Their lightweight, high strength, low profile, corrosion resistance, and ease of application provide additional advantages in cases where steel- or concrete-based solutions are bulky and impractical.

Structural strengthening using FRP carbon fiber has been used around the world since the late 1980s [4]. In Kenya, it was first introduced and used successfully in 2011, when the leading manufacturers SIKA Kenya and BASF Kenya were established in the country. FR composites are high-strength materials that have been used in the aerospace, marine, and automotive industries. Recently, there has been a significant increase in the use of FRP composites in civil engineering applications to repair and retrofit existing structures, particularly concrete and masonry buildings and bridges [5-6]. Locally, FRP carbon fiber technology has been used successfully to strengthen deficient structures and, recently, it was used to shear reinforce columns at the Hazina Trade Center in 2018.

Although the use of carbon fiber to reinforce concrete has been under massive development, little research has been done in Kenya. Most of the time, Kenyan applicators rely on the information given by manufacturers through product data sheets or webinars. Several studies have been conducted throughout the world on the use of carbon fiber in concrete strengthening. The studies focused on the application of FRP in structural strengthening due to its advantages, such as durability, versatility, low cost, and practicability. The fiber matrix interface is essential for the performance of fiber-reinforced composites. In [7], it was shown that the bond behavior between CFRP and concrete depends on the roughness of the concrete surface. In [8-9], it was deduced that the bond behavior between CFRP and concrete depends on the moisture conditions. In [10], it was concluded that the state of the base concrete (substrate) affects the bonding properties with FR composites, as the roughness of the concrete substrate has a crucial impact on the bond strength between the FRP and the concrete interface. In [11], it was found that the shear-friction mechanism that occurs in the interface zone is directly related to the roughness of the concrete crack interfaces. In [12], poor bonding in the interface zone was shown to lead to two main failures of the concrete overlays: debonding and cracks. In [13], it was established that to improve the mechanical properties of the concrete-resin interface zone, the concrete surface should be modified using different methods. In [14], it was concluded that different methods can be used to modify the concrete surface.

According to the International Concrete Repair Institute (ICRI), there are 10 distinct concrete surface profiles, named CSP 1 to CSP 10. The lower profile numbers are smoother (CSP 1 is nearly flat), and the higher numbers get progressively rougher. Although many studies have been conducted on the application of FRP in structural strengthening focusing on the bond behavior between CFRP and the concrete substrate, there are no conclusive studies on the concrete surface profile and the moisture condition that gives the highest bond strength between them. This study aimed to examine the profile of the concrete surface and the moisture conditions that demonstrate the best bond strength between CFRP and the concrete substrate. This study examined four different concrete surfaces, unprepared (CSP 1), grinded (CSP 2), sanded (CSP 3), and scabbed (CSP 8), all under various moisture conditions: dry concrete substrate, saturated surface dry concrete substrate, and wet concrete substrate. The objective was to evaluate the effect of concrete substrate condition on the strength properties of a retrofitted fiber-reinforced composite. The results can guide the construction industry on the best concrete surface and moisture conditions when using CFRP to strengthen concrete.

II. MATERIALS AND METHODS

The materials used to create the concrete mixture were Ordinary Portland Cement (OPC) Type 32.5 N, river sand, coarse aggregate with a maximum aggregate size of 20 mm, and clean water. Materials were sourced from a reliable supplier while clean drinking water was obtained for the concrete formulation from the JKUAT laboratory. Unidirectional 300 g carbon fiber wraps, also denoted 300 C, obtained from Sika Kenya Limited, including the Sikadur 300 resin recommended by the manufacturer, were used with the wrapping fabric. A mix design conforming to C25-grade concrete was formulated [15]. Table I represents a summary of the design of the formulated mix.

TABLE I. SUMMARY OF MIX DESIGN FOR C25 GRADE CONCRETE

Nominal strength (N/mm^2)	**Batch weights per 1m3 at SSD (Kg)**			**Water (Kgs)**	**Water cement ratio**	**Actual slump (mm)**	**Ratios for batching by weight C : RS : B**		
	10/20mm aggregates	**River sand**	**Cement (32.5 N)**						
25	1070	600	450	210	0.47	45	1	1.3	2.4

The constituent concrete materials were mixed in a tilting drum mixer (laboratory type) until a homogeneous concrete mix was formulated. Fine aggregate and cement were added and mixed for two minutes. The coarse aggregate was then added and mixed for another two minutes before continuously adding water and mixing for another two minutes. The concrete mix was then removed from the mixer and used to cast the cylindrical concrete specimens. The slump test readings for all the formulated batches were found to be within the designed range of 30-60 mm, indicating a medium degree of workability.

The wet concrete was added to the cylindrical molds in 3 layers, after which tapping was performed to compact the concrete. This process was repeated until the cylindrical molds were full. The interior of the cylindrical molds was ensured to be oiled to prevent the concrete from sticking to the sides. A total number of 66 cylindrical concrete specimens were prepared, 30 of which were used as control samples and 36 were adopted as study samples. All cylindrical specimens had a slenderness ratio equal to 2 (height H = 200 mm and outer diameter D = 100 mm). The concrete specimens were then cured in water for a period of 7 and 28 days to achieve the desired design strengths before further preparation and testing. The cured study specimens were grouped into four clusters so that each one had 9 specimens. Then, each specimen was labeled using a permanent marker on the top and bottom.

Four different concrete surfaces, following ICRI Guideline No. 310.2R–2013, were examined: grinded (CSP 2), sanded (CSP 3), scabbed (CSP 8), and unprepared (CSP 1), all under various moisture conditions: dry concrete substrate (DS), saturated surface dry concrete substrate (SSD), and wet concrete substrate (WS). The CSP 1 profile was achieved using oiled steel molds that ensured that the specimens had a uniform and smooth surface finish. The CSP 2 profile was achieved by grinding the surface of specimens using an abrasive tool with a diamond disc to achieve a fairly smooth finish. The CSP 3 profile, also known as light shortblast, was achieved by sanding, while the CSP 8 profile was achieved by hacking the surfaces of the specimens using a pointed chisel and hammer. The dry surface samples were cured in air for at least 24 hours before subsequent preparations and testing, while the wet samples were cured in water for at least 24 hours before subsequent preparations and tests. The samples with the saturated surface dry condition were cured in water for 24 hours, then removed from the water and cured in the air for 1 hour, so that the surface particles were dry but the interior particle voids were saturated with water.

Fig. 1. Study specimens grouped and labeled.

Fig. 2. Cutting the wrapping fabric into the desired sizes.

Fig. 3. Wrapped study specimens.

After surface preparation, the samples were wrapped in one layer of 300 g unidirectional carbon fiber wrap from Sika Kenya Ltd. The selected wrapping fabric was cut with special scissors in the desired sizes. The epoxy resin was mixed and applied to the surfaces of the prepared specimens before the application of the wrapping fabric in the wet epoxy resin. Excess air was removed using rollers and the specimen was left to cure. The application method followed the manufacturer's specifications. The carbon-wrapped samples were then subjected to compressive strength tests to assess the effects of concrete substrate conditions on the strength properties of a retrofitted fiber-reinforced composite. The specimens were placed centrally between the compressive test machine plates, and then a load was applied at a uniform rate, with approximately a stress rate of 12 MPa/min until the test specimen failed.

III. RESULTS AND DISCUSSION

Table II shows the compressive strength results. It can be observed that there is a general strength increase from the CSP 1 to the CSP 8 substrate condition, as shown in Figure 4. Roughness imparts an additional surface area with which the adhesive can contact when forming a bond. Normally, the adhesive is absorbed by capillary attraction into the added surface pits, increasing the surface area of bond contact, and this is the reason why the CSP 8 substrate condition demonstrated the highest bond behavior with the FRP carbon fiber wrap. The wet moisture condition shows the best bond behavior between the concrete interface and the FRP for all but the CSP 1. Interfaces where the substrate surface is prewetted such that moisture movement from the epoxy is minimized, lead to reduced porosity and increased hydration on the epoxy side of the interface, which increases bond strength. This explains why the wet moisture condition showed the best bond behavior, as shown in Figure 5.

TABLE II. COMPRESSIVE STRENGTH OF THE SAMPLES

Specimen category	**Specimen ref. no.**	**Height of specimen (mm)**	**Diameter of specimen (mm)**	**Failure load (kN)**	**Compressive strength (N/mm^2)**	**Equivalent cube compressive strength (N/mm^2)**	**Average compressive strength (N/mm^2)**	**Standard deviation strength (N/mm^2)**
Unprepared (CSP 1)	CSP 1-DS 1	200	100	264.30	33.65	42.06	41.25	0.80
	CSP 1-DS 2	200	100	259.20	33.00	41.25		
	CSP 1-DS 3	200	100	254.20	32.36	40.45		
	CSP 1-WS 1	200	100	251.70	32.04	40.05	37.97	2.11
	CSP 1-WS 2	200	100	238.89	30.41	38.01		
	CSP 1-WS 3	200	100	225.23	28.67	35.84		
	CSP 1-SSD 1	200	100	252.13	32.10	40.12	41.09	1.95
	CSP 1-SSD 2	200	100	272.28	34.66	43.33		
	CSP 1-SSD 3	200	100	250.19	31.85	39.81		
Grinded (CSP 2)	CSP 2-DS 1	200	100	231.84	29.51	36.89	34.65	2.40
	CSP 2-DS 2	200	100	219.58	27.95	34.94		
	CSP 2-DS 3	200	100	201.88	25.70	32.13		
	CSP 2-WS 1	200	100	269.92	34.36	42.95	42.69	1.18
	CSP 2-WS 2	200	100	274.67	34.97	43.71		
	CSP 2-WS 3	200	100	260.12	33.11	41.39		
	CSP 2-SSD 1	200	100	248.61	31.65	39.56	39.57	0.54
	CSP 2-SSD 2	200	100	252.02	32.08	40.10		
	CSP 2-SSD 3	200	100	245.27	31.22	39.03		
Sanded (CSP 3)	CSP 3-DS 1	200	100	272.34	34.67	43.34	41.89	2.28
	CSP 3-DS 2	200	100	246.73	31.41	39.26		
	CSP 3-DS 3	200	100	270.69	34.46	43.08		
	CSP 3-WS 1	200	100	265.62	33.82	42.27	42.39	0.65
	CSP 3-WS 2	200	100	262.74	33.45	41.81		
	CSP 3-WS 3	200	100	270.76	34.47	43.09		
	CSP 3-SSD 1	200	100	217.68	27.71	34.64	37.42	2.43
	CSP 3-SSD 2	200	100	245.97	31.31	39.14		
	CSP 3-SSD 3	200	100	241.88	30.79	38.49		
Scabbed (CSP 8)	CSP 8-DS 1	200	100	268.69	34.21	42.76	42.25	2.23
	CSP 8-DS 2	200	100	277.59	35.34	44.17		
	CSP 8-DS 3	200	100	250.16	31.85	39.81		
	CSP 8-WS 1	200	100	274.28	34.92	43.65	43.86	0.61
	CSP 8-WS 2	200	100	279.94	35.64	44.55		
	CSP 8-WS 3	200	100	272.63	34.71	43.38		
	CSP 8-SSD 1	200	100	189.42	24.11	30.14	28.72	2.71
	CSP 8-SSD 2	200	100	160.87	20.48	25.60		
	CSP 8-SSD 3	200	100	191.16	24.34	30.42		

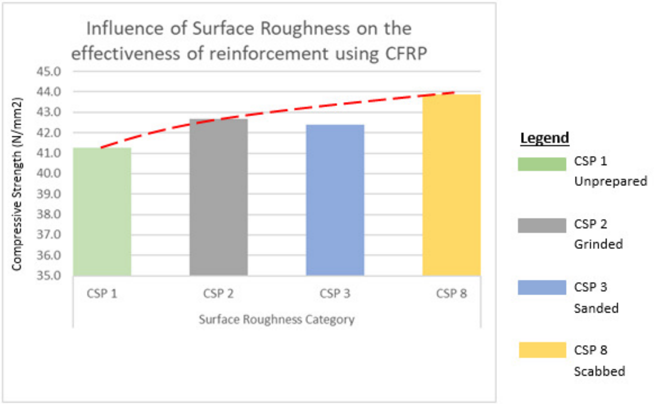

Fig. 4. Influence of grinded, sanded, scabbed, and unprepared concrete surfaces on the effectiveness of reinforcement using CFRP.

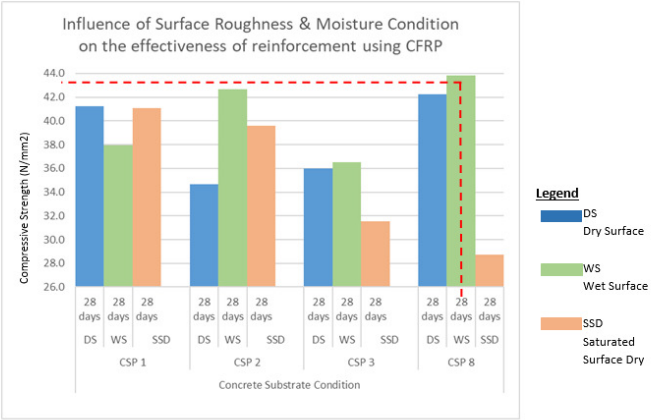

Fig. 5. Influence of surface roughness and moisture condition on the effectiveness of CFRP reinforcement.

IV. CONCLUSIONS

The compressive strength results showed that the concrete surface and moisture condition had a significant effect on the bond strength between CFRP and the concrete interface. Among the four specimen categories, from CSP 1 to CSP 8, the latter in wet moisture conditions demonstrated the highest bond strength between CFRP and the concrete substrate. It was observed that there was a general increase in strength from CSP 1 to CSP 8 concrete substrate condition. Roughness creates additional surface area with which the adhesive can make contact when forming a bond. Normally, the adhesive is absorbed by capillary attraction into the added surface pits increasing the surface area of bond contact, and this is the reason why the CSP 8 concrete substrate condition demonstrated the highest bond strength with the CFRP wrap. In addition, the wet moisture condition showed the best bond behavior between the concrete interface and FRP reinforcement for all except the CSP 1 concrete substrate condition. A prewetted substrate surface interface, such that moisture movement from the epoxy is minimized, leads to reduced porosity and increased hydration on the epoxy side of the interface, directly contributing to the increased bond strength. The CSP 8 surface roughness in wet moisture condition demonstrated the best bond strength due to the combined factors of increased surface area for adhesive bond contact and increased hydration on the adhesive side of the interface. This directly contributed to the increased bond strength.

Furthermore, it was inferred that CFRP wrapping led to a significant increase in concrete strength of samples cured for 7 and 28 days compared to some unwrapped concrete control samples. The samples cured for 7 days showed a 116% strength increase after carbon wrapping while the samples cured for 28 days showed a 79% strength increase. When introducing a CFRP to a concrete member, the section is confined and the stresses are unable to lead to typical failure mechanisms. The addition of a carbon fiber wrap increases the capacity of the concrete and provides additional strength in axial, bursting, and flexural loading.

This study helps understanding the impact of the concrete substrate condition on the strength properties of fiber-reinforced composites. The findings on the concrete substrate surface that gives the highest bond strength will enhance and increase the use of carbon fiber for structural strengthening and rehabilitation of structures, especially in this era of increased infrastructural development in the country. In addition, most of the old and unsafe structures that would otherwise have been demolished will be secured for continued use. This study also provides engineering professionals and contractors with valuable information on structural strengthening using CFRP. This will also improve the service life and maintenance of structures that require strengthening to reach full design life and will ensure and guarantee a safe built environment for all.

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