J Fail. Anal. and Preven. (2024) 24:402–413
https://doi.org/10.1007/s11668-023-01850-1

ORIGINAL RESEARCH ARTICLE

Mechanical and Corrosion Investigations of Bond Behavior in Reinforced Concrete with Varying Parameters

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Submitted: 5 November 2023 / in revised form: 5 December 2023 / Accepted: 13 December 2023 / Published online: 12 January 2024

Abstract The bond strength between reinforcing steel bars and cement concrete plays significant role in the structural performance for civil infrastructure. This work presents the bond performance of steel and concrete as interfacial shear strength, with the inclusion of effects of specimen diameter on embedment length, different aggregate grading and corrosion. The experimental procedure for proposed study includes a series of pullout tests on reinforced concrete cylindrical specimens with embedded steel bar. Cylindrical concrete specimens with varying specimen diameters with respect to different embedment lengths, changing the aggregate grading pattern, i.e., well and gap graded were casted and said effects on bond strength were evaluated through a pullout test. The corrosion effect is also studied through an accelerated corrosion process. The test results revealed that the diameter of the specimen and the embedment length substantially impact the bond strength between reinforcing bars and concrete. Due to the increasing surface area and mechanical interaction between the bar and the surrounding concrete, the bond strength increased as the diameter decreased. The bond performance of well-graded aggregates was effective compared to gap-graded aggregates. Moreover, the study found that as the number of corrosion days increased, the bond strength of corroded reinforcing bars considerably decreased. The results contribute essential insights to the field of reinforced concrete structures and can aid engineers and researchers in designing durable and reliable infrastructure systems.

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Keywords Bond strength · Accelerated corrosion · Pullout test · Reinforced concrete · Half-cell potential · Aggregate grading

Introduction

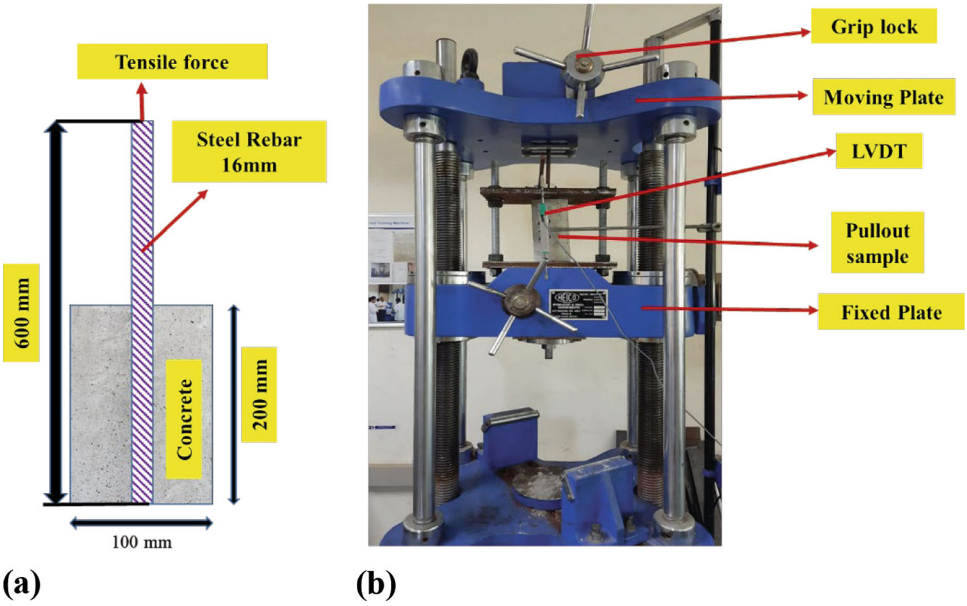
Reinforced concrete is one of the world's most widely utilized construction materials due to its exceptional durability, flexibility, and structural strength. The strength of the bond between the reinforcing bar and the surrounding concrete matrix is critical to the integrity and performance of reinforced concrete buildings [1–3]. Understanding and improving bond strength is critical for the safety and lifespan of civil engineering structures like buildings, bridges, and dams. It is an essential characteristic that determines structural stability, load transmission, serviceability, durability, and even seismic performance [4]. Understanding the complexity of bond strength is critical not only for engineers and academician but also for construction practitioners since it directly influences the safety and performance of infrastructure projects. Form the last four decades, many Researchers aspire to contribute to the growth of knowledge in structural engineering by unraveling the complexities of bond strength and encouraging safer and more robust structures for the benefit of society. The complex interaction of significant factors impacting the bond strength between reinforcing bars and concrete significantly improves the serviceability of reinforced concrete structures, particularly emphasizing specimen diameter, aggregate grading, and the influence of corrosion.

The embedding length of rebar in concrete structures is an essential factor that directly impacts the construction's structural integrity, load-bearing capacity, and overall performance [5]. The part of a reinforcing device, such as a rebar or anchor bolt embedded into the concrete matrix, is known as the embedded length. Numerous published investigations have shown the critical impact that development length plays in improving bond strength within these structures [6–8]. Several studies have indicated that increasing bond length leads to significant improvements in bond strength [9, 10]. Remarkably, the bond strength could reduce significantly as the anchoring length increases. This phenomenon is characterized by a negative correlation in which increasing anchoring length results in a significant drop in bond strength [11, 12]. Past researchers focuses on the factors such as effect of size of bar [13], Type of bars [14], Grade of concrete [15], Types of concrete [16], Confinement [17], Cover thickness [18] on bond strength. The present research offers insights into the importance of embedment length in reinforcing steel-concrete constructions. However, there is still a significant study gap in the influence of embedment length relative to specimen diameter on bond strength [19]. While much research has been conducted to investigate the relation between development length and bond strength, they frequently fail to account for variability in specimen diameter, which can be a critical factor impacting the bond behavior. There is a need for dedicated research into how changing embedment lengths affect bond behavior of various specimen diameters.

The interaction of cement matrix and aggregate is critical for concrete's bond shear strength (and hence the interlocking force between steel and concrete), durability, and overall performance. Aggregates, which generally account for 60-75% of the total volume of concrete, play an essential role in determining the material's behavior. Another crucial factor of aggregate grading (having or missing successive sizes of aggregate) governs the packing and workability of the concrete mix. The majority of researchers focuses on the size of the aggregates on bond strength [20]. But cost effective and optimized design of grading of aggregate is not addressed properly for interfacial bond strength. Over past decades' researchers focus on the replacement of aggregates, i.e., recycled aggregate [21], slag [22], Light weight aggregate [7] on bond strength. The previous literature primarily focuses on the influence of aggregate size on bond behavior of reinforced concrete with some emphasis on replacing aggregates with other materials. However, there is a considerable limited study in complete understanding of the effect of aggregate grading on bond strength between concrete and steel. While aggregate size has been widely investigated, the mixture and distribution of aggregates in the concrete mix, as defined by grading, has received little attention. There is very limited research on the variations of aggregate grading on bond characteristics of steel and concrete. The aggregate grading impacts the distribution of forces inside the concrete, which impacts bond resistance.

The corrosion of reinforcing bars buried in concrete is critical in civil engineering and building sustainability [23]. Corrosion of reinforcing bars is a global phenomenon affecting concrete buildings' durability, safety, and performance. Concrete constructions deteriorate due to various environmental conditions such as humidity, chloride ions, carbonation, and harsh chemicals [24]. The susceptibility of the reinforcing bars toward corrosion, which affects the durability and strength to reinforced concrete buildings [25]. Due to its exposure to corrosive environments, steel is vulnerable to various types of corrosion mechanisms. Metallic corrosion in aqueous solutions usually involves simultaneous reduction and oxidation events at cathodic and anodic active sites, respectively, because of the transfer of charges at the metal-solution interface. Furthermore, the surrounding physical, chemical, or biological variables exacerbate the issue. Particularly in the oil and natural gas sectors, prolonged contact to acidic environments is more harmful to metals than alkaline or situations neutral to both acids and alkalis. The gradual deterioration of the concrete cover is one of the critical challenges related to this corrosion process, which can have significant consequences for the structural integrity of the overall system [26, 27]. Corrosion of rebars, an ongoing problem in many constructions, can have a substantial impact on their bond strength [28]. Over the past few years, much research has been committed to investigating the bond performance of reinforced concrete (RC) structures in the context of reinforcement corrosion. This research has delved into numerous aspects of RC components, including examinations of Bond strength-slip curves and corrosion rates [29–31]. Corrosion impacts bond strength deterioration differently across various kinds of reinforced bar. The rust deposition on bars causes volume expansion and subsequent cracking of the surrounding concrete matrix throughout the deterioration process. Corroded steel can reduce the bond strength and ultimately endanger the substantial element's structural integrity. For the overall efficacy and durability of existing structures and creating measures to prevent corrosion-induced degradation, it is crucial to conduct an extensive study on how corrosion affects bond strength.

To address this gap, a series of experiments were undertaken to explore the influence of specimen diameter on embedded length, aggregate grading, and the impact of corrosion to offer insightful information on bond properties. The prime focus of the study is to improve the structural integrity of reinforced concrete elements by promoting safer and more enduring building techniques. The following objectives were conducted to enhance the strength and durability of reinforced concrete structures.



(a) (b)

Fig. 1 (**a**) dimensions (**b**) specimen details

Table 1 Material properties of cement

Specific gravity	Soundness (mm)	Initial setting time (min)	Final setting time (min)	Consistency (%)
3.145	7.5	37	528	32

Table 2 Material properties of aggregates

Fine aggregates			Coarse aggregates		
Fineness modulus	Specific gravity	Water absorption	Fineness modulus	Specific gravity	Water absorption
4.36	2.12	6.38	5.64	3.15	1.67

Table 3 Mix design of concrete

W/C Ratio	Materials (Kg/m^3)			
0.55	Cement	Coarse aggregates	Fine aggregates	Water
	360	552	1303	198

i. Investigations of bond behavior between steel and concrete with specimen diameter and embedded length variations.
ii. To assess the impact of aggregate grading on bond strength through various aggregate sizes and distributions.
iii. To explore a detailed investigation of the impact of corrosion periods on bond strength subjected to accelerated corrosion processes.

The significance of the current study is relevant in the fields of construction engineering and infrastructure development. The bond strength between reinforcing bars and concrete is a significant aspect of reinforced concrete construction to improve structural integrity and safety. Understanding how this bond strength changes with specimen diameter, aggregate grading, and the effect of corrosion is critical for designing and analyzing infrastructure durability in various environmental circumstances. This research addresses fundamental bond behavior and has practical implications for the construction industry, assisting engineers and designers in making informed material selection and structural design decisions to ensure the long-term stability and safety of concrete structures. Additionally, since corrosion is a problem that frequently affects concrete structures, particularly in harsh environments, examining its effect on bond strength offers insights into the preservation and rehabilitation of existing infrastructure, ultimately enhancing the sustainability and longevity of our built environment. The novelty of the research focused on investigating bond behavior between steel and concrete using different Specimen Diameter to embedment length and different grading of aggregates to optimize the mix design. The study also investigates the corrosion aspects of reinforced concrete through bond strength and half-cell potential.

This paper discusses the bond behavior, significant aspect of reinforced concrete construction structural integrity and safety. Understanding how this bond strength changes with specimen diameter, aggregate grading, and the effect of corrosion is critical for designing and analyzing infrastructure durability in various environmental circumstances. Concrete samples were cast and the effect specimen diameter to embedded length, effect of corrosion and aggregate grading were tested in accordance with

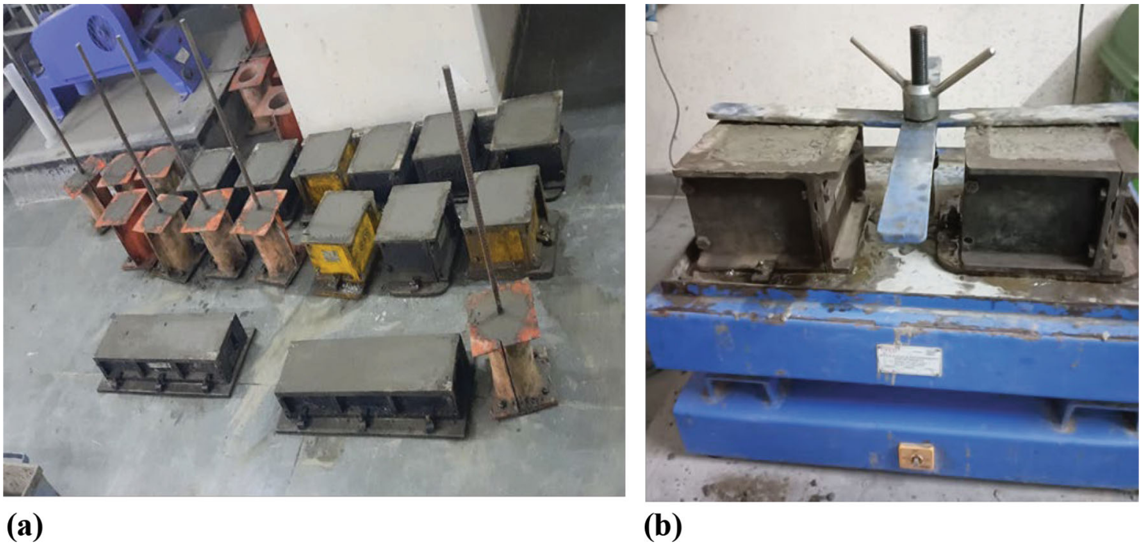


Fig. 2 Detail preparation of samples (**a**) filling of concrete and curing (**b**) vibration of Concrete

ASTM standards. In all overall this study, offers insights into the preservation and rehabilitation of existing infrastructure, ultimately enhancing the sustainability and longevity of our built environment.

Experiments and Methods

This section covers Specimen Preparation, testing methods, i.e., compressive strength and pullout testing, accelerated corrosion testing, of reinforced concrete samples. Three sets of experiments were carried out, comprising pullout tests on different parametric variations and corrosion. These tests aimed to investigate how grading of aggregates and corrosion affects bond performance, additional details are provided below.

Specimen and Materials Preparation

Three cylindrical specimens of dimensions 100 × 200 mm were prepared with a deformed steel bar embedded into it. Fig. 1a and b shows the detail dimensions and specimen details for pullout testing. Standard concrete mix with a set percentage of OPC 43 cement, river sand, coarse aggregates, and water were utilized. The properties of cement, Sand, and coarse aggregates are outlined in Tables 1 and 2. The concrete mix should adhere to building standards and requirements. The cement concrete mix design followed the guidelines of BIS 10262:2009 [32]. Table 3 shows the mix proportions of concrete adopted in this research. 16 mm diameter high-quality steel reinforcing bars with 500 Mpa yield strength are utilized in accordance with IS 1786 (2008) [33]. The bars should be free of visible defects and contaminants. Cylindrical concrete specimens with various specimen diameters to embedment length ratios will be cast. A 600 mm long steel rebar was inserted vertically through a hole in the bearing plate to accommodate its position. The samples will be cast in a steel mold to maintain uniform dimensions and surface polish. After the molds have been filled with the concrete mixture, they will be subjected to vibration for 15–20 s. This vibration procedure ensures the concrete settles uniformly within the mold and eliminates any air gaps or holes that might weaken the finished specimen. Figure 2b illustrates the vibration of the concrete to remove air bubbles trapped within the mixture. The specimens were left undisturbed for 24 hours to cure to improve the material's setting and initial strength (see Fig. 2b). The samples were precisely demolded after a 24-h curing period to ensure the specimens kept their intended form and integrity.

Table 4 Parameters for test specimen

Type of bar	Diameter (mm)	Embedment length (mm)	Compressive strength (Mpa)
Deformed	16	100	29
Deformed	16	100	31.20
Deformed	16	100	29.32

Testing Methods

Compressive Testing

The compressive strength of concrete of size 150 × 150 × 150 mm was calculated by the parameters

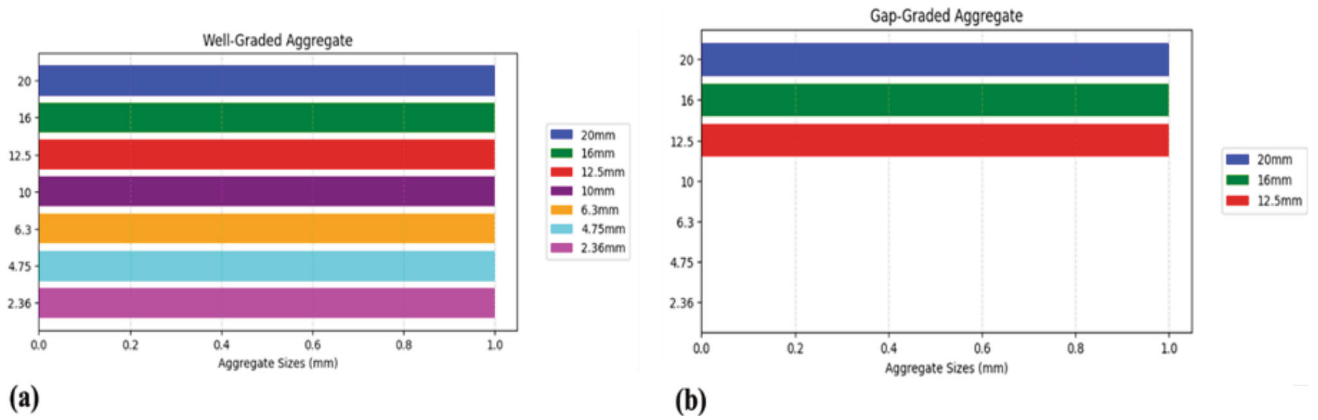


Fig. 3 Different grading of aggregates (**a**) well graded (**b**) gap graded

outlined in IS 516 (BIS 1959). A compressive testing machine with a load capacity of 2000 kN will be employed. Each specimen will be placed in the testing machine with care. The loading rate was rigorously maintained at 0.1 kN per sec during testing, ensuring consistent and precise results. Three independent samples were averaged to acquire the final compressive strength values. Table 4 provides the compressive strength values for three different samples.

Pullout Testing

The cylindrical samples were prepared in accordance with ASTM C234 [34]. Each specimen was a concrete cylinder with a single steel reinforcement bar in the middle. Fig. 1a shows that the steel bar was extended about 350 mm above the top of the concrete cylinder to give sufficient length for connection to the testing apparatus. A steel bar hidden length of 100 mm was kept within the concrete to allow for bond strength growth. The casting was done in three stages, with each layer vibrated for 15–20 s to ensure adequate compaction. The top layer was flattened to provide an excellent surface finish. The samples were securely wrapped in plastic to avoid moisture ingression. After a 24 h curing, the samples were demolded and cured in a water tank for 28 days at standard temperature and humidity. Conventional pullout tests were conducted on the three cylindrical specimens. An automated Universal Testing Machine (UTM) recording system of load capacity 400 kN was used, outfitted with high-precision linear variable differential transducers (LVDTs) to constantly monitor the slip of the rebar when subjected to the applied load and stress. During the tests, the loading rate was held constant at 0.1 kN/s. To ensure an equal distribution of loading pressure over the specimen surfaces, the specimens were firmly positioned between two plates, with leather sheets inserted over the plates and the sample surfaces. Moreover, the reinforcing bar will be slowly pulled out of the concrete at a constant rate until it fails. The maximum applied load and displacement will be measured. The load-displacement data obtained from the pullout tests will be collected and analyzed to calculate the bond strength values.

Aggregate Grading

Aggregate grading plays crucial role to improve strength, durability, workability and prevents segregation and bleeding. A well-graded mix has aggregate particles dispersed uniformly across various sizes with a maximum size of 20 mm and below. In contrast, gap grading has a considerable gap or void between sizes of aggregate particles and below 12.5 mm size of aggregates were omitted. Figure 3a and b shows the representation of well and gap graded aggregates, respectively.

Specimen Diameter to Embedded Length

The specimen diameter plays a crucial role in the distribution of stresses and effective load transfer at the interface. Figure 4a and b shows the schematic diagram for 100 mm and 150 mm cylindrical specimens embedded with 16 mm diameter steel bars. The effect of specimen diameter on different embedment lengths, such as 8 d, 10 d, and 12 d, was evaluated using pullout testing. The bond strength vs slip curves were analyzed and discussed through bond strength values.

Corrosion Testing

To simulate corrosion, a controlled accelerated corrosion procedure will be conducted for the chosen specimens. The samples were thoroughly cleaned to eliminate impurities or surface contaminants and dried to ensure their initial weight was precisely noted. The samples were treated to an

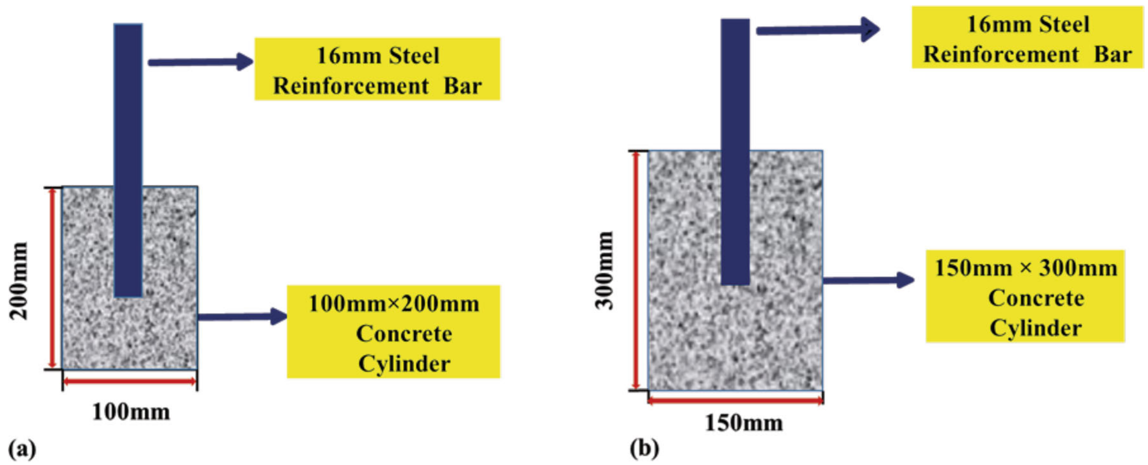


Fig. 4 Specimen diameter to embedded length (**a**) 100 mm diameter (**b**) 150 mm diameter

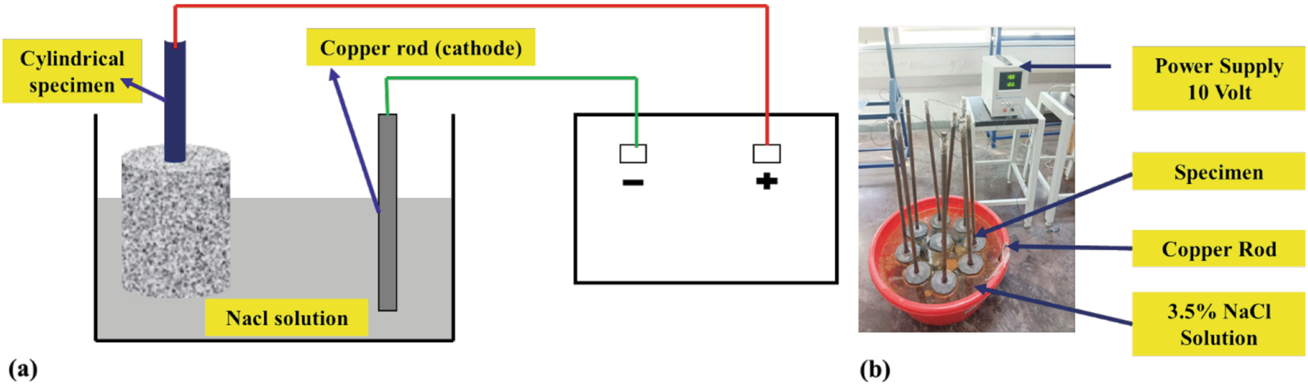


Fig. 5 Accelerated corrosion (**a**) schematic diagram (**b**) actual set up

accelerated corrosion environment by immersing them in a 3.5% NaCl (solution and incorporating an impressed current. Figure 5a and b depicts the schematic diagram and actual setup for accelerate corrosion. The steel bar acted as the anode, and a copper rod served as the cathode. An external power supply of 10 V was connected to the copper rod and steel bars. A regulated electric current was applied to the steel reinforcing bars to aid corrosion. The amplitude of the current was controlled and monitored during the experiment. The specimens will be exposed to a corrosive environment for a set period. The ultimate bond strength was evaluated for different days using pullout test. Figure 6a and b shows schematic diagram and actual set up for Half-cell potential testing. The setup comprised a working electrode submerged in the test electrolyte, a reference electrode, and a counter electrode. This setup enabled us to measure and study the electrochemical behavior of the system. Table 5 shows the guidelines for the active corrosion in accordance with ASTM C876 [35]. These standards provide a valuable benchmark for measuring corrosion severity and controlling material selection and maintenance methods in various industrial applications.

Results and Discussions

Interfacial bond strength is considered a significant design parameter in reinforced concrete constructions to enhance its overall performance. This research looks at the effect of specimen diameter, aggregate grading, and corrosion behavior on the bond strength. These experimental results and discussion will give important insights into the elements influencing bond behavior in concrete structures. Figure 7 shows the average bond strength vs slip curve for 3 different samples. The plot shows a clear pattern, demonstrating how bond strength varies as slip rises. As slip grows, average bond strength decreases consistently, indicating that the bond interface weakens as the material's slippage or deformation [36, 37]. This finding is important for evaluating the integrity of concrete structures because it

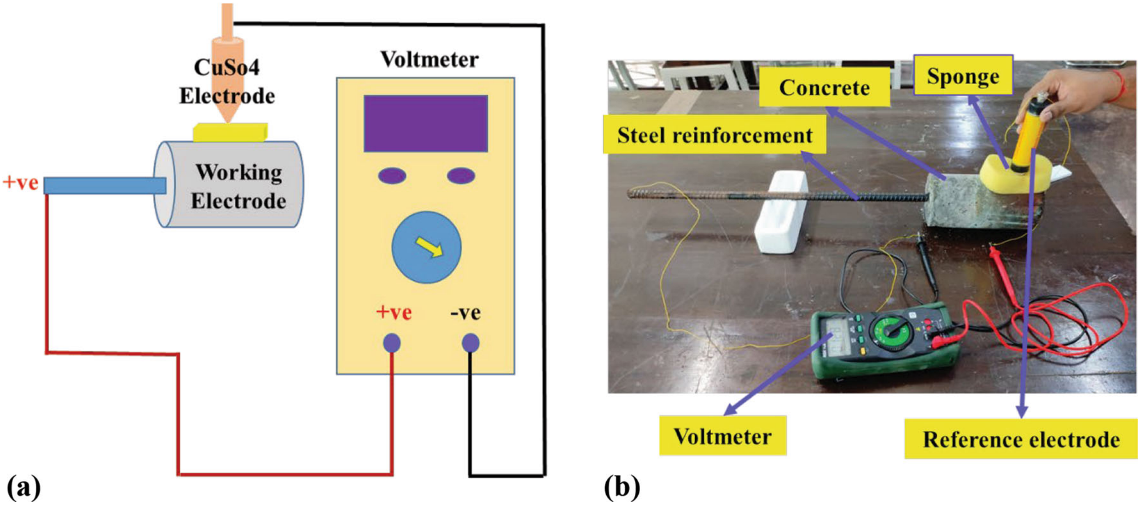


Fig. 6 Half-cell potential set up (**a**) schematic Diagram (**b**) actual set up

Table 5 Guidelines for active corrosion [35]

Half-cell potential reading (mV)	Percentage chance of active corrosion (%)
< -350	90
-200 to -350	50
> -200	10

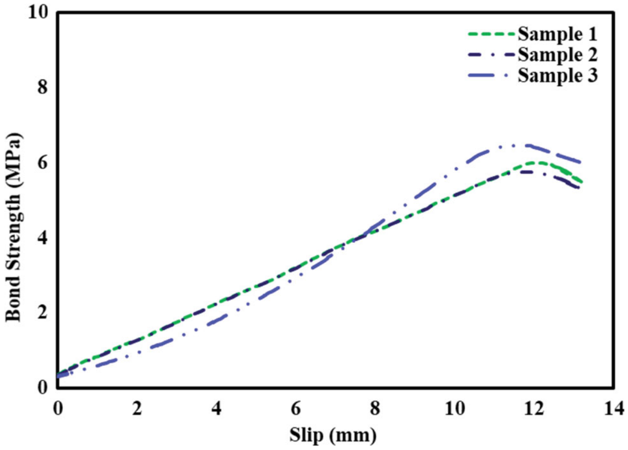


Fig. 7 Bond strength vs Slip curve between steel and concrete

emphasizes the need to maintain enough bond strength to ensure the stability and performance of concrete structures under varying load circumstances. The ultimate bond strength was calculated by using the following Eq 1.

$$\tau = \frac{P_u}{\pi l d} \tag{Eq 1}$$

where P_u is the maximum load at failure. l is the embedded length of steel bar, and d is the diameter of rebar.

Effect of Aggregate Grading

In this section, the Authors studied the influence of well and gap graded aggregates on steel-concrete bond strength. The concrete specimens using both aggregates were tested, and the maximum load at slip was recorded using pullout tests. Figure 8a and b shows the average bond Strength-Slip values obtained for both well grading and gap grading concrete mixes. This research's findings indicate a significant variation in bond value for different aggregate grading. It has been found that well-graded aggregates contribute to producing a superior interlocking mechanism with steel reinforcement. This improved mechanical interlock adds to increased bond strength. Gap-graded aggregates have voids between specific aggregate sizes and might result in less contact between the aggregate and the steel surface. Especially compared to well-graded aggregates, the small contact area decreases bond strength. The presence of voids in gap-graded aggregates may help less frictional forces at the steel-concrete contact. Friction is an important component of bond strength, and a reduction in frictional resistance can result in lower bond strength values. Well-graded aggregates have higher bond strength and are commonly preferred in structural applications where bond strength is critical. On the other hand, Gap-graded aggregates may be used in situations where workability and other criteria are more important than bond strength.

Effect of Specimen Diameter to Embedded Length

In this study, the author examined the variation among cylindrical specimen diameter (100 and 150 m) and embedded length (8 d, 10 d, and 12 d) on the bond strength between steel and concrete. This study intends to provide significant insights into specimen diameter and

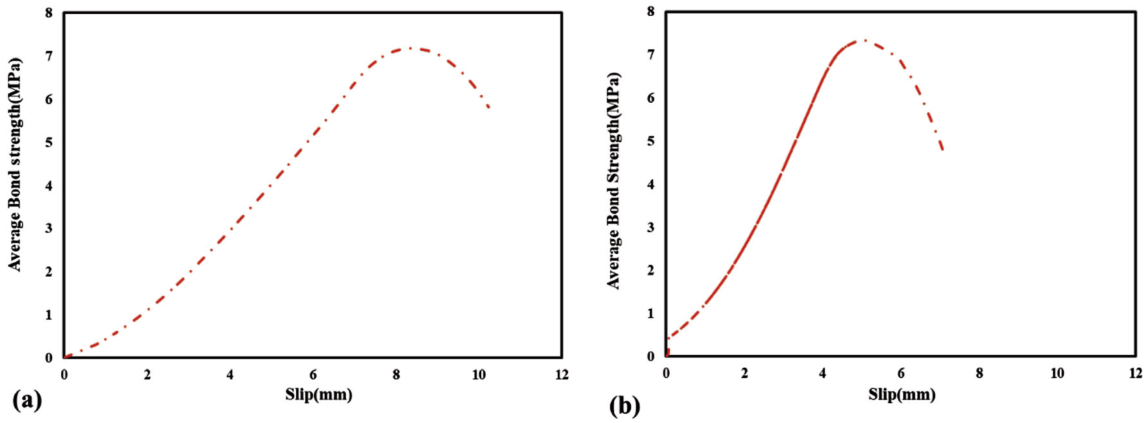


Fig. 8 Average bond strength vs. Slip curve between steel and concrete (**a**) gap-graded aggregates (**b**) well-graded aggregates

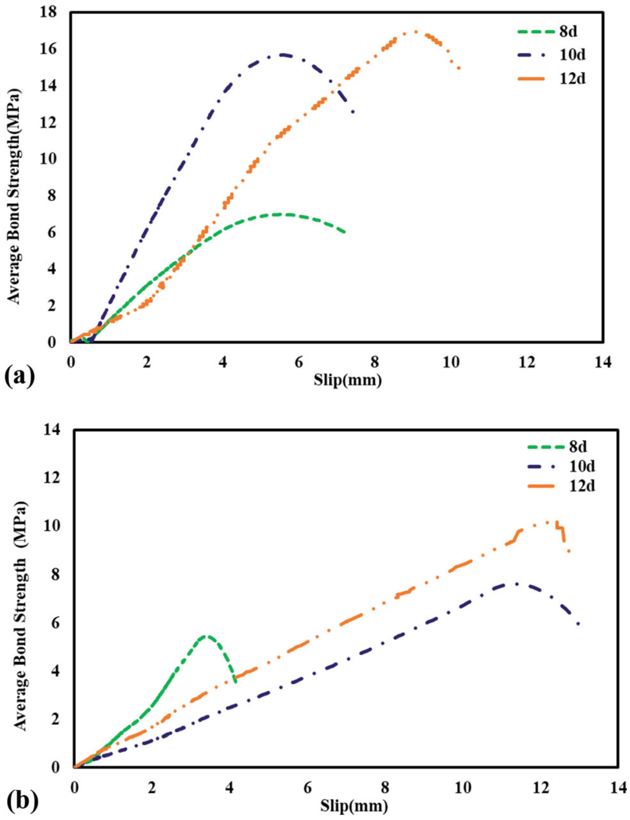


Fig. 9 Bond strength-slip curves for different embedment length to (**a**) 150 mm dimeter (**b**) 100 mm diameter

embedded length impact on bond strength through varying these factors. Figure 9a and b shows the bond strength-slip behavior for 150 and 100 mm diameter cylindrical specimen. It has been seen that bond strength was significantly greater for 150 mm diameter samples compared to 100 mm diameter for specimens with an anchored length of 8 d. This difference can be due to the 150 mm specimens' higher surface area accessible for bond formation. Similar patterns were found for embedded lengths of 10 d and 12 d, with the 150 mm diameter specimens consistently demonstrating greater bond strength values than the 100 mm diameter samples. An increase in embedding length from 8 to 12 d resulted in a substantial improvement in bond strength for the 100 and 150 mm diameter specimens. This result indicates that in smaller diameter specimens, a longer embedment length leads to increased bond strength. The finding of the result shows that specimen diameter and embedded length substantially influence the bond properties. A larger specimen diameter offers an additional surface area for creating strong concrete and steel interfaces. This result indicates that 150 mm specimen diameter have increased bond strength levels, as larger specimens less susceptible to confinement effects, which can improve bond strength even more.

Effect of Corrosion on Bond Strength

Corrosion of steel reinforcement in concrete structures is a serious issue that could risk integrity and durability of RCC structures. In the present investigation, the authors employed an accelerated corrosion setup to explore the effect of corrosion on the bond strength at different exposure times, i.e., 3, 14, and 30 days. The findings and discussion of this study provide information about how different phases of corrosion impact bond strength. Specimens were exposed to a corrosive environment over 3, 14 and 30 days. Fig. 10. shows the effect of accelerated corrosion before testing. Pullout testing was performed after each corrosion exposure days to assess the influence on the bond performance (see Fig. 11.). The findings clearly show a considerable decrease in bond strength as corrosion exposure time rises. The noticed reduction in bond strength can be due to many corrosion-related variables. Steel rebars produce rust and corrosion by-products on their surface as corrosion develops, which may disrupt the adhesion between the steel and the surrounding concrete. This rust

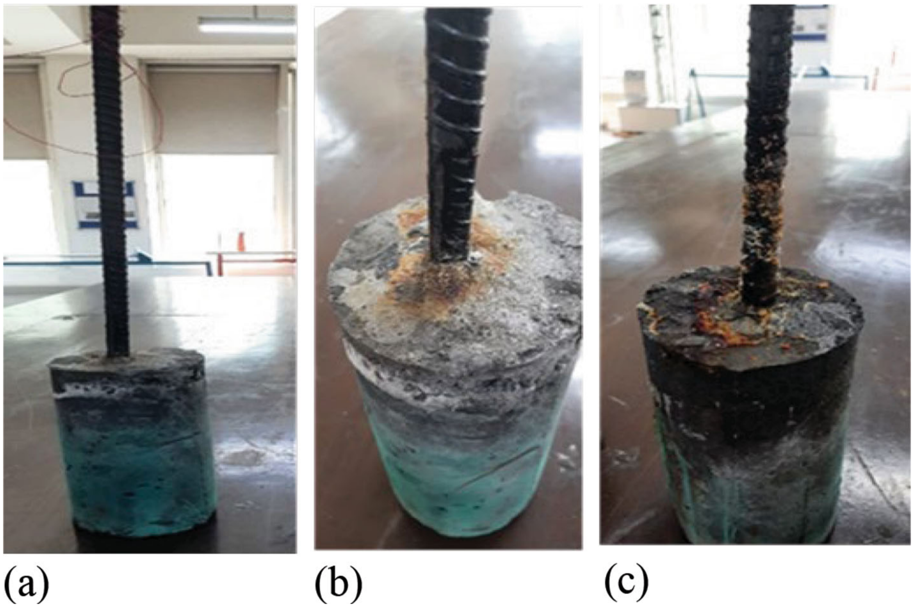


Fig. 10 Effect of Accelerated corrosion before testing (**a**) 3 Days (**b**) 14 Days (**c**) 30 days

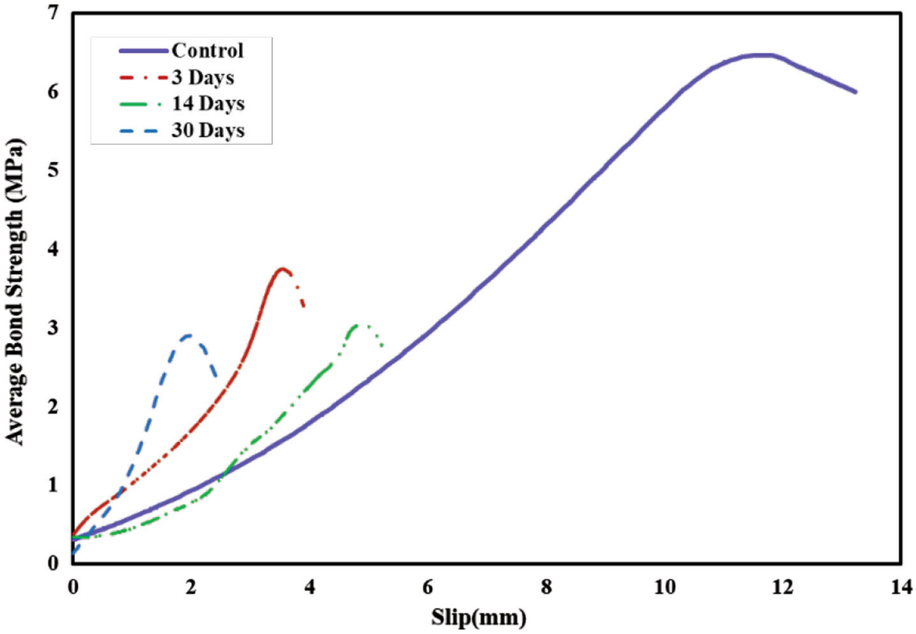


Fig. 11 Bond Strength-Slip curve at different corrosion periods

coating is a barrier between steel and concrete, lowering the effective contact area and bonding. Furthermore, the growth of rust can strain the surrounding concrete, causing cracking and weakening the bond. The development of voids and fractures in the surrounding concrete can also reduce bond strength. Figure 12. shows the different failure modes with days of exposure. As the corrosion process grows, these faults can spread, resulting in the start and propagation of damage along the material's longitudinal axis. This eventually leads to a splitting failure when the material can no longer allow for the imposed stresses. Figure 13. compares bond strength values for different exposure days with the control sample. The graph demonstrates that the bond strength of control specimen, which was not exposed to corrosion, mainly remained steady during the test. However, the samples subjected to accelerated corrosion showed a noticeable loss in bond strength as the exposure days progressed. The reduction in bond strength with increased exposure days might be due to corrosion on the steel within the concrete. Corrosion of the steel reinforcement causes rust to develop and the steel to expand, producing internal stresses inside the concrete matrix. These internal stresses, in turn, reduce the bond strength, affecting the material's structural stability.

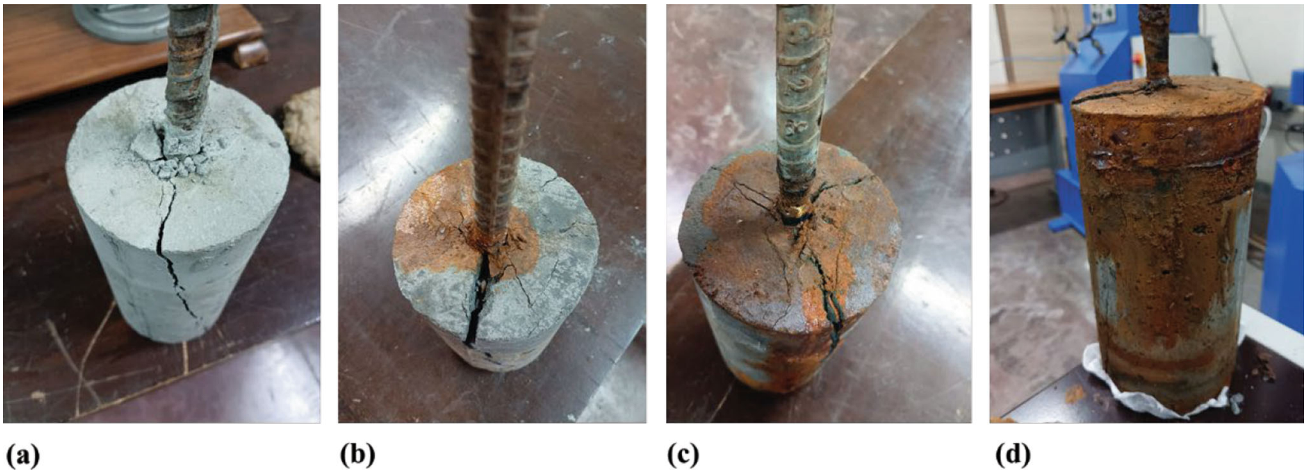


Fig. 12 Failure modes after testing (**a**) Control (**b**) 3 Days (**c**) 14 Days (**d**) 30 Days

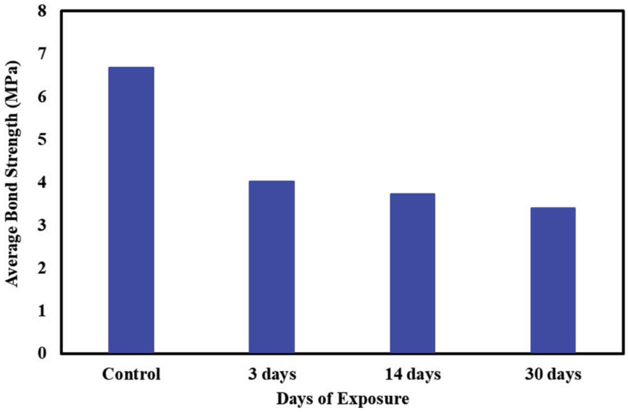


Fig. 13 Comparison of bond strength w.r.t days of exposure

Table 6 Half-cell potential values

Days of exposure (days)	Average half-cell potential value (mV)	Probability of corrosion (%)
3	− 125	10
14	− 327	50
30	− 430	90

Then, the study extended to check the half-cell potential values for different days of corrosion.

Table 6 shows the average half-cell potential values collected at various exposure times, as well as the corrosion conditions associated with them. The half-cell potential values are an essential indication of the corrosion behavior of the material being studied. The corrosion potential values in this investigation were measured in millivolts (mV) and were tracked during three independent exposure periods: 3, 14, and 30 days. The average half-cell potential value was − 125 mV after the 3-day exposure period, representing a 10% chance of corrosion. The high potential value in the negative range indicates that the material had a low likelihood of corrosion after a brief exposure period. This finding points to the development of a protective oxide layer on the material's surface that served as a barrier against corrosive chemicals during the earliest stages of exposure. The average half-cell potential value was − 327 mV after 14 days of exposure. As the guidelines indicate, there is a 50% likelihood of corrosion, and this decrease in potential value shows a greater vulnerability to corrosion. The negative change in potential indicates that the protective oxide layer allows corrosive processes to proceed more rapidly. After 30 days of exposure, the average half-cell potential value dropped to − 430 mV, with a 90% chance of corrosion. This abrupt drop in potential value indicates severe corrosion conditions. The material's surface most likely undergone significant corrosion, resulting in a loss of its protective characteristics. When long-term durability is a concern, the significant rise in the chance of corrosion emphasizes the crucial relevance of preventative measures or material selection. It is critical to note that the relationship between half-cell potential levels and corrosion likelihood is well-established in corrosion research. The greater the half-cell potential, the greater the possibility of corrosion. As a result, the patterns seen in this study are consistent with what is expected of materials in corrosive environments.

Conclusions

In this study, the author performed strength and durability tests to explore important factors affecting the bond properties. Pullout testing was conducted for all the parameters affecting the bond strength. The major effects of specimen diameters to embedment length, aggregate grading and corrosion exposure days were studied. The experiments produced insightful results to understand the bond behavior in adverse conditions. The major findings drawn from this research are as follows.

- The increase in the ratio of specimen diameter to embedment length improves load transmission capacity, resulting in a stronger and stable bond behavior.
- Well-graded aggregates produce a superior interlocking mechanism with the steel reinforcement, resulting in stronger bond strength. In contrast, gap-graded aggregates had lower bond strength values due to voids and reduced contact area between the aggregates and the steel surface.
- Furthermore, the study emphasized the impact of corrosion exposure days on bond strength. Higher corrosion exposure days of reinforced concrete have considerably lower bond strength than control sample. This emphasizes the vital need of applying suitable corrosion prevention methods in corrosive situations in concrete buildings. Implementing corrosion-resistant materials, coatings, or cathodic protection systems may drastically increase the lifetime and performance of reinforced concrete buildings, lowering maintenance costs and increasing safety.
- The results obtained from half-cell potential values indicated that the material had a low risk of corrosion, with an average half-cell potential of − 125 mV after 3 days. However, after 14 days, the potential declined to − 327 mV, indicating a 50% probability of corrosion, and after 30 days, it dropped even further to − 430 mV, indicating a 90% chance of corrosion.

The study can further have extended to evaluate the behavior of bond strength for natural corrosion progression. Future research will also focus on long-term corrosion impacts and prevention, effect of fatigue loading on the bond characteristics of RCC structures. This research can guide engineering techniques, resulting in durable and sustainable infrastructure.

Conflict of interest The research conducted with integrity and ethical guidelines declares no conflicts of interest.

References

1. F. Yan, Z. Lin, M. Yang, Bond mechanism and bond strength of GFRP bars to concrete: a review. Compos. B Eng. **98**, 56–69 (2016)
2. M. Abubakar, I.S.A. Abdulmajeed, Characterization, mechanical properties and probabilistic failure analysis of reinforcement bars produced from scraps in southern and northern region of Nigeria. J. Fail. Anal. Prev. **23**(3), 1232–1241 (2023)
3. S. Krishnaveni, S. Rajendran, A state of the art on characterization and application of artificial neural networks on bond strength between steel rebar and concrete. Constr. Build. Mater. **354**, 129124 (2022)
4. M.H. Akeed, S. Qaidi, H.U. Ahmed, R.H. Faraj, A.S. Mohammed, W. Emad, A.R. Azevedo, Ultra-high-performance fiber-reinforced concrete. Part IV: durability properties, cost assessment, applications, and challenges. Case Stud. Constr. Mater. **17**, e01271 (2022)
5. S.M. Pour, M.S. Alam, Investigation of compressive bond behavior of steel rebar embedded in concrete with partial recycled aggregate replacement, in *Structures*, vol 7, (Elsevier, New York, 2016), p.153–164
6. H.T. Li, A.J. Deeks, X.Z. Su, D.S. Huang, Tensile bond anchorage properties of Australian 500N steel bars in concrete. J. Central South Univ. **19**(10), 2718–2725 (2012)
7. M. Lachemi, S. Bae, K.M.A. Hossain, M. Sahmaran, Steel–concrete bond strength of lightweight self-consolidating concrete. Mater. Struct. **42**, 1015–1023 (2009)
8. L. Butler, J.S. West, S.L. Tighe, The effect of recycled concrete aggregate properties on the bond strength between RCA concrete and steel reinforcement. Cem. Concr. Res. **41**(10), 1037–1049 (2011)
9. M. Sabău, I. Pop, T. Oneţ, Experimental study on local bond stress-slip relationship in self-compacting concrete. Mater. Struct. **49**, 3693–3711 (2016)
10. Z. Zhou, P. Qiao, Bond behavior of epoxy-coated rebar in ultra-high performance concrete. Constr. Build. Mater. **182**, 406–417 (2018)
11. C.C. Li, G. Kristjansson, A.H. Høien, Critical embedment length and bond strength of fully encapsulated rebar rockbolts. Tunn. Undergr. Space Technol. **59**, 16–23 (2016)
12. D.Y. Yoo, J. Je, H.J. Choi, P. Sukontasukkul, Influence of embedment length on the pullout behavior of steel fibers from ultra-high-performance concrete. Mater. Lett. **276**, 128233 (2020)
13. M.J.R. Prince, B. Singh, Bond behaviour of deformed steel bars embedded in recycled aggregate concrete. Constr. Build. Mater. **49**, 852–862 (2013)
14. D. Ertzibengoa, S. Matthys, L. Taerwe, Bond behaviour of flat stainless steel rebars in concrete. Mater. Struct. **45**, 1639–1653 (2012)
15. I. Fernandez, M. Etxeberria, A.R. Marí, Ultimate bond strength assessment of uncorroded and corroded reinforced recycled aggregate concretes. Constr. Build. Mater. **111**, 543–555 (2016)
16. F.M. de Almeida Filho, M.K. El Debs, A.L.H. El Debs, Bond-slip behavior of self-compacting concrete and vibrated concrete using pull-out and beam tests. Mater. Struct. **41**(6), 1073–1089 (2008)
17. T.K. Hassan, A. Mantawy, J. Soliman, A. Sherif, S.H. Rizkalla, Bond characteristics and shear behavior of concrete beams reinforced with high-strength steel reinforcement. Adv. Struct. Eng. **15**(2), 303–318 (2012)
18. H.A. Bengar, F.A. Zarrinkolaei, Effect of steel fibers and concrete cover on bond behavior between steel deformed bar and concrete under high temperature, in *Structures*, vol 32, (Elsevier, New York, 2021), p.1507–1521
19. N. Venugopal, L. Emmanual, P. Sunagar, L. Parida, M. Sivaranjani, M. Santhanakrishnan, Enhancing the mechanical characteristics of the traditional concrete with the steel scrap. In Journal of Physics: Conference Series (Vol. 2272, No. 1, p. 012031). IOP Publishing. (2022)
20. S. Iqbal, N. Ullah, A. Ali, Effect of maximum aggregate size on the bond strength of reinforcements in concrete. Eng. Technol. Appl. Sci. Res. **8**(3), 2892–2896 (2018)
21. K. Pandurangan, A. Dayanithy, S.O. Prakash, Influence of treatment methods on the bond strength of recycled aggregate concrete. Constr. Build. Mater. **120**, 212–221 (2016)
22. Y. Ling, K. Wang, W. Li, G. Shi, P. Lu, Effect of slag on the mechanical properties and bond strength of fly ash-based engineered geopolymer composites. Compos. B Eng. **164**, 747–757 (2019)

23. L. Chung, S.H. Cho, J.H.J. Kim, S.T. Yi, Correction factor suggestion for ACI development length provisions based on flexural testing of RC slabs with various levels of corroded reinforcing bars. Eng. Struct. **26**(8), 1013–1026 (2004)
24. A.S. AL-Ameeri, M.I. Rafiq, O. Tsioulou, Combined impact of carbonation and crack width on the chloride penetration and corrosion resistance of concrete structures. Cem. Concr. Compos. **115**, 103819 (2021)
25. S. Subash, L. Parida, U. Singh, S. Moharana, Corrosion inhibitors for enhanced strength, durability, and microstructure of coastal concrete structures. Mater. Res. Express. **10**(7), 075101 (2023)
26. F. Tondolo, Bond behaviour with reinforcement corrosion. Constr. Build. Mater. **93**, 926–932 (2015)
27. M.G. Stewart, Mechanical behaviour of pitting corrosion of flexural and shear reinforcement and its effect on structural reliability of corroding RC beams. Struct. Saf. **31**(1), 19–30 (2009)
28. C.Q. Li, S.T. Yang, M. Saafi, Numerical simulation of behavior of reinforced concrete structures considering corrosion effects on bonding. J. Struct. Eng. **140**(12), 04014092 (2014)
29. D. Banić, D. Grandić, D. Bjegović, Bond characteristics of corroding reinforcement in concrete beams. In Application of Codes, Design and Regulations: Proceedings of the International Conference held at the University of Dundee, Scotland, UK on 5–7 July 2005 (pp. 203-210). Thomas Telford Publishing. (2005)
30. A.A. Almusallam, A.S. Al-Gahtani, A.R. Aziz, Effect of reinforcement corrosion on bond strength. Constr. Build. Mater. **10**(2), 123–129 (1996)
31. L. Chung, J.H.J. Kim, S.T. Yi, Bond strength prediction for reinforced concrete members with highly corroded reinforcing bars. Cement Concr. Compos. **30**(7), 603–611 (2008)
32. BIS: 10262-2009; Indian concrete mix design guidelines. Bureau of Indian Standards: New Delhi, India, (2009)
33. BIS; IS. Indian Standard for high strength deformed steel bars and wires for concrete reinforcement; Bureau of Indian Standards: New Delhi, India, (2008)
34. A.P. Clark, Bond of concrete to reinforcing bars. J. Proc. **46**, 161–184 (1949)
35. ASTM C876-91 1999 Standard test method for half-cell potentials of uncoated reinforcing steel in concrete 03 1–6
36. F.I. Ismail, Y.M. Abbas, N. Shafiq, G. Fares, M. Osman, L.A. Hussain, M.I. Khan, Investigation of the impact of graphene nanoplatelets (GnP) on the bond stress of high-performance concrete using pullout testing. Materials. **14**(22), 7054 (2021)
37. K.S. Ahmed, M. Shahjalal, T.A. Siddique, A.K. Keng, Bond strength of post-installed high strength deformed rebar in concrete. Case Stud. Constr. Mater. **15**, e00581 (2021)