# Effect of Reinforcing Bar Contamination on Steel-Concrete Bond During Concrete Construction

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Synopsis:

During concrete construction, form oil, bond breaker, concrete splatter and other types of contaminants often contaminate reinforcement. Current specifications and quality control measures require the removal and clean up of these contaminants before the placement of concrete due to a concern of a reduction in bonding capacity. This is costly, labor intensive, and may not be necessary.

Currently, there is limited research on the effect of reinforcing bar contamination on the bond between the deformed steel reinforcing bar and concrete. Because of this lack of data, specifications are conservative and require the removal of the contaminant. Inspectors often cite ACI 301-96, *Standard Specifications for Structural Concrete*, which states, "When concrete is placed, all reinforcement shall be free of materials deleterious to bond." If it could be conclusively proven that this level of care is unnecessary, the construction industry would benefit greatly.

To address the effects of contaminants on bond characteristics of deformed steel reinforcing bars, a preliminary study was completed at the University of Missouri-Rolla. The research program focused on three contaminants often seen during construction: form oil, bond breaker and concrete splatter. Other variables included size of reinforcing bar, strength of concrete and epoxy versus uncoated reinforcing bar. This paper will provide the experimental program and test procedures as well as the test results and observations. The results reveal that in the majority of situations tested, the ultimate bond stress was not significantly affected by the three contaminants tested. In some cases, the bond breaker and form oil affected the smaller epoxy coated bars, while the effect of concrete splatter was insignificant.

Keywords: Bond Strength; Construction Specifications; Reinforcing Bars; Contaminants; Reinforced Concrete; Slippage

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## INTRODUCTION

A good bond between steel deformed reinforcing bar and concrete in concrete structures is crucial for structural and serviceability performance. If this bond is inadequate, behavior and failure characteristics will be altered. The bond mechanism allows the forces to be transferred between the concrete and steel.

In concrete construction, many types of contaminants are present on the site, such as form oil for coating the forms and bond breaker used in tilt-up construction. The reinforcement could be contaminated during construction if care is not taken. If contaminated, there is concern regarding the bond strength and specifications are in place to guide the action to be taken.

When constructing reinforced concrete (RC) structures, inspectors have the duty to enforce several specifications dealing with concrete construction (1,2). One of the goals of the specifications is to maintain a clean and safe construction environment. Often, reinforcing bar is subjected to various construction contaminants, such as form oil or mud during concrete construction, and the specifications require the reinforcing bar to be cleaned prior to placing the concrete. The American Concrete Institute (ACI) provides several of these specifications. ACI 301-96 (1) states, "When concrete is placed, all reinforcement shall be free of materials deleterious to bond." This specification also addresses form oil specifically when it states, "Do not allow formwork release agents to contact reinforcing steel or hardened concrete against which fresh concrete is to be placed." When dealing with oil and concrete splatter or mortar, ACI's *Manual of Concrete Inspection* (2) says, "reinforcement should be clean, and oil or non-adherent mortar which has been spilled on it should be cleaned off." Again, the primary concern of these specifications is assuring a good bond, but do the contaminants reduce the bond strength enough to warrant these specifications? Without detailed research into this issue, most construction specifications are conservative and require the removal of these contaminants from the reinforcing bar. This is time-consuming, costly, and may be unnecessary (3).

Previously, several studies have been performed in regard to the variables that affect bond strength, including the effect of the amount of concrete cover, casting position, slump and consolidation on epoxy-coated reinforcing bar (4), and the effect of rust and scale (5,6). It was found that up to a certain degree of rust, the bond was not significantly reduced and the specifications were relaxed. These specifications now recognize that slightly rusted steel reinforcing bar does not cause a significant reduction in the bond stress and allows contractors to use this reinforcing bar without having to first remove the rust. This saves the contractor considerable time and money without significantly affecting the quality and strength of the RC structure.

## Principle of Bond Between Reinforcing Bar and Concrete

Bond is defined as a force transfer between two materials (7). Bond behavior involves the bond stresses, transfer mechanisms and ultimately the complete failure mode. Bond stress is defined as the shear stress at the steel-concrete interface, which by transferring the load between the reinforcing bar and surrounding concrete, modifies the steel stresses (8). The average bond stress is typically represented as $\mu_{avg}$ and its equation is:

$$\mu_{avg} = \frac{\Delta f_s d_b}{4 l_b}$$

where: $\mu_{avg}$ = average bond stress, $\Delta f_s$ = change of steel stress over unit length, $d_b$ = diameter of reinforcing bar, and $l_b$ = embedment length.

There are several mechanisms that transfer the load between the concrete and steel. The three primary mechanisms are chemical adhesion, mechanical interlock and frictional resistance. Each method contributes to the overall bond strength in varying amounts depending on the type of reinforcing bar and conditions under which the concrete is placed. For deformed steel reinforcing bar, the greatest contribution comes from the mechanical interlock, with the frictional and chemical bonds both helping to a lesser extent. The bearing of concrete on the steel ribs causes the mechanical interlock. As the forces are transferred, the concrete is placed under a shearing stress; thus eventually causing bond failure. With plain (smooth) reinforcing bar, the chemical and frictional bonds would be the primary mechanisms, with the mechanical interlock almost non-existent.

### Bond Test Methods

Several test methods are commonly used to determine steel-concrete bond strength. One method is the pullout test specified by RILEM (9). The advantages of this test are the easy setup and simple specimens, yet a concern is the additional confinement provided by the compression induced into the specimen around the anchorage area. Furthermore, it is not representative of a beam because reinforcing bars are in tension and concrete is in compression. A flexural test avoids the additional confinement and more realistically simulates the embedment in the tension zone in concrete beams, where both reinforcing bar and concrete are in tension, in addition to the presence of shearing forces and dowel action. Two flexural tests are common, one specified by RILEM (10) and the other specified by ASTM (11). The RILEM beam test is a simply supported beam with a gap in the middle, allowing for easy calculations of the tension force and ultimately the bond stress. The ASTM A944 Beam-End test is a rectangular specimen placed into flexure through a cantilevering action. Both of these test methods are widely used in testing laboratories.

The test method selected for this research program was the RILEM Bond Test for Reinforcing Steel-Beam Test, Specification Number 7-II-28 D (10). This test method was chosen over other methods for several reasons. A flexural test was preferred over a direct pullout test because it more realistically simulates the actual conditions in a beam or slab. The RILEM beam test was chosen over the Beam-End method for its simplicity. In the authors' opinion, both the RILEM test and Beam-End test provide similar results and similar testing characteristics.

## RESEARCH SIGNIFICANCE

There is a need for research into the specific problem of the effect of reinforcing bar contamination on the steel-concrete bond in reinforced concrete structures. Structural and construction engineers are often conservative and require the reinforcing bar to be cleaned before placing the concrete. The engineers do not know the extent of the effect of contaminants on bond stress. This study will provide a basis for more research into this topic, with the goal of eventually having sufficient data to confirm or deem unnecessary the need for the current requirements. If it can be shown that some of the most common construction contaminants do not have a detrimental effect on the steel-concrete bond, the specifications could then be revised to possibly allow a specific amount of reinforcing bar contamination, resulting in considerable savings to the concrete construction industry.

## EXPERIMENTAL PROGRAM

Several factors influence the bond strength of the steel-concrete composite. These factors are related to both the concrete (compressive strength, amount of cover, etc.) and reinforcing bar (size, surface coating, embedment length, rib face angle, etc.). Additionally, the type of contaminant (form oil, mud, bond breaker, concrete splatter, rust, etc.) may produce different bond characteristics. For this preliminary study, four variables were included. They were the surface coating condition (epoxy coated or uncoated), size of reinforcing bar, concrete compressive strength, and type of contaminant. Of the many types of contaminants, the study focused on three: water-based form-release agent, a water-based bond breaker, and concrete splatter. These contaminants are commonly seen during construction operations. The effects of rust have been already studied and the specifications modified accordingly.

The test program consisted of 32 tests, with three replicate specimens per test for a total of 96 specimens. The surface coating was varied between epoxy coated and uncoated. The two sizes of reinforcing bar chosen were #4 (13 mm) and #7 (22 mm). Nominal concrete compressive strengths at 28 days of 4,000 psi (28 MPa) and 7,000 psi (48 MPa) were selected. Instead of the 7,000-psi (48 MPa), a higher strength would have provided a clearer understanding of the effect of concrete strength, yet to attain this and maintain workability, admixtures most likely would have been used. Use of admixtures was not desirable in order to avoid any possible unforeseen chemical interaction between the contaminants and admixtures. The contaminants were applied along the entire embedment length, simulating the worst-case situation. The specimens were batched in groups of 12 beams, with the type of contaminant being the only variable per batch. The test program is summarized in Table 1.

The specimen identification code consisted of four characters. The first letter is the surface coating condition, either epoxy coated (C) or uncoated (U). The second number in bold is the reinforcing bar size, either #4 (13 mm) or #7

(22 mm). The third number is the 28-day compressive strength, either a 4 for 4,000 psi (28 MPa) or a 7 for 7,000 psi (48 MPa). The fourth letter is the type of contaminant applied to the reinforcing bar, C for control (clean), S for concrete splatter, and B for bond breaker and F for form oil. The number in parenthesis is the number of replicates tested.

## Test Specimen

The test specimens used in this study were fabricated according to RILEM Standards (10). Figure 1 illustrates the configuration of the test specimen. The specimen was a flexural beam separated in the middle with the reinforcing bar crossing the gap. The two rectangular prisms were joined together with a steel hinge in the compression zone and the reinforcing bar to be tested was located in the tension zone. The reinforcing bar was embedded into the center of each prism with a length of 10 times its diameter ($10d_b$), as specified by RILEM. PVC tubing was provided outside the $10d_b$ length to prevent the concrete from bonding to the steel along the non-embedded portion of the reinforcing bar. The dimensions of the beam, casting position and additional reinforcement were as specified by RILEM. The beams were cured per RILEM specification for 28 days at approximately 60% relative humidity and $20 \pm 2^oC$.

## Materials

The concrete mixture proportions used in this study are given in Table 2. The mixture used Type I portland cement, 9/16 in. (14.3 mm) nominal maximum size, clean, crushed limestone from the Gasconade Formation in Missouri, and fine aggregate sand from the Little Piney River in central Missouri. The water was tap water from Rolla Municipal Utilities in Rolla, Missouri.

The reinforcing steel used was ASTM A615-96A Grade 60 (12). The epoxy coating was applied per ASTM A775-96 (13). The tested average yield stress was determined at 443 MPa (64.2 ksi) and the average tensile strength was 713 MPa (103.5 ksi). The uncoated reinforcing bar was free from any rust or other contaminants and the epoxy coated reinforcing bar had no chips or scratches in the epoxy.

Three contaminants were used in this study: namely bond breaker, form oil and concrete splatter. The bond breaker was a water-based lifting agent that is used in tilt-up construction. The form oil was a surface consolidating water-based form release agent that is used in precast and poured concrete applications. The concrete splatter had the same mixture proportions as the mortar portion of the concrete in the specimen, simulating a multiple lift pour where this contamination often occurs.

The method of applying these contaminants was an attempt to simulate field conditions. The form oil and bond breaker were applied 30 minutes prior to placing the concrete using a brush to get complete coverage. The concrete splatter was applied 18 hours before placement of concrete. From a series of trial batches with varying setting times, 18 hours was chosen as the worst-case situation because at this point the concrete has hardened, yet not achieved a good bond to the steel. The splatter was dropped (or splattered) onto the bar while slowly rotating the bar to ensure complete coverage. Figs. 2 and 3 show the form oil and concrete splatter contaminated reinforcing bar, respectively, prior to concrete placement.

### Test Setup and Procedure

The beam tests were conducted using a 110-kip (500 kN) MTS servo-valve controlled machine. All loads were applied using ram stroke control to better observe the failure and post-failure behavior. The free-end slip was measured using Linear Variable Differential Transformers (LVDT's) placed on each end of the reinforcing bar. The beams were transported from the curing location to the testing machine using an overhead crane and lifting system designed to avoid relative movement between the two halves of the beams. Placing a wooden block in the hinge location and bolting two boards to either side of the beam restrained the two halves from moving relative to each other.

The beams were tested under four-point loading in accordance with the RILEM specification with the load being applied symmetrically to both halves of the beams (Fig. 4). The LVDT's were attached securely to the beam, assuring that only relative slip between the reinforcing bar and concrete was measured. As one side of the beam failed, a restraint device was placed on that end of the reinforcing bar to prevent further slip and to allow the other half to reach failure.

## RESULTS

### Concrete Compressive Strength

The compressive strength of the concrete was determined according to ASTM specification C39. However, four cylinders instead of three were tested per batch of concrete. The design strengths selected for this study were 4,000 psi (28 MPa) and 7,000 psi (48 MPa); however, the actual strengths were 4,780 psi (33 MPa) and 6,710 psi (46 MPa), respectively.

The actual strength for the 7,000-psi (48 MPa) mixture is slightly low and the mixture proportions could have been adjusted or admixtures added to get higher strengths. Because of possible unforeseen chemical interactions with the contaminants, admixtures were not used. Workability requirements prevented the w/c from being lowered. The workability was a concern with the RILEM test because of the additional reinforcement required in the beam.

## Bond Stress Calculations

The bond stress on the bonded portion of the bars was determined in relation to the applied load and geometry of the test setup. The relationship between the applied load and the bond stress can be shown to be:

$$\tau_b = \frac{T}{\pi d l_b} = \frac{\frac{Pa}{2jd}}{\pi d l_b}$$

Where $P$ = Applied Load, $a$ = distance between support and load, $jd$ = lever arm, $d$ = reinforcing bar diameter, and $l_b$ = embedment length.

Substituting the following values; $l_b = 10d$, $a$ = 450 mm (17.7 in) and $jd$ = 160 mm (6.3 in) then

$$\tau_b = \frac{P}{7.11\pi d^2}$$

where P is in kN and d is in mm

For a 13 mm (#4) bar the average bond stress is calculated:

$$\tau_{b,13mm}(MPa) = \frac{P(kN)}{3.77}$$

For a 22 mm (#7) bar the average bond stress is calculated:

$$\tau_{b,22mm}(MPa) = \frac{P(kN)}{10.81}$$

## Bond Test Results

The results of the RILEM beam tests are summarized in Fig. 6. The ultimate bond stresses of the various tests did vary somewhat. The statistical significance of the amount of variance is presented later.

From Fig. 6, it is evident that #4 (13 mm) bars show a higher bond strength compared to that of #7 (22 mm) bars. All #7 (22 mm) bars exhibited bond-splitting failure, where the #4 (13 mm) bars exhibited a combination of pullout and bond splitting failures. Note that both #4 (13 mm) and #7 (22 mm) bars were tested under the same embedment length of $10d_b$. Comparable results for both #4 (13 mm) and #7 (22 mm) cases could have been achieved if bond-splitting failure were avoided. Yet, the specimens, as tested, more realistically simulate the case of a beam or slab in terms of moderate concrete cover and, presence of shearing forces and dowel actions. Therefore, the bond spitting failure noticed in # 7 (22 mm) cases are acceptable.

Bond stress-slip curves were generated for each beam. A typical set of bond stress-slip curves for a beam set is presented in Fig. 7. The general shape of the curves depended on the type of failure, however, the differences were minimal. Two failure modes were observed: bond splitting and bond pullout, with the majority of failures being bond splitting. Bond splitting is well documented for steel deformed reinforcing bar (7). It is characterized by a small amount of slip producing the bond splitting, followed by further slip and finally a complete loss of bond. The bond splitting is caused when a primary crack propagates to the surface and several secondary cracks form near the lugs of the deformed reinforcing bar. These cracks are caused by the wedging action of the reinforcing bar being pulled through the concrete. Typically, a larger bar with a small amount of concrete cover will fail in bond splitting. Bond pullout only occurred in a limited number of #4 (13 mm) epoxy coated bars. This failure is characterized by an increasing amount of slip until the bar pulls out of the concrete and the bond strength lessens considerably. While the general shape of the stress-slip curves varied little, the bond stress magnitude did vary depending on the variables being tested, most notably the reinforcing bar size. In the set of curves shown in Fig. 7, two specimens failed in bond splitting, while the third failed in bond pullout. A side view of a beam that failed in bond splitting is given in Fig. 8.

## Statistical Analysis of Data

An inspection of the bond stress results shows the following. Bond stresses were higher for: 1) the #4 (13 mm) bars (all 32 tests), 2) higher compressive strength mixture (31 tests), 3) control compared to bond breaker

(8 out of 8 tests), 4) control compared to form release agent (7 out of 8 tests), 5) splatter over control (6 out of 8 tests), and 6) plain reinforcing bar over epoxy coated (22 out of 32 tests). The statistical significance of these trends was investigated using JMP, which is produced by the SAS Institute (14). The statistical tests used for comparing the data included Dunnett's t-Test and a Least Squares Model.

Prior to using Dunnett's t-Test, the data was first tested for statistical outliers and normality. Two tests were used to check outliers, the 3*$\sigma$ test, where $\sigma$ is the standard deviation of the test group, and the Dixon Q test. Both methods indicated no significant outliers. Normality was checked using a Q-Q Plot at an $\alpha$ (confidence level) = 0.05. Normality indicates if the data has a normal distribution. The data was somewhat non-linearly distributed along the Q-Q Plot, yet because the number of tests was large enough, the Central Limit Theorem applies and the data distribution is considered approximately normal. From the distribution of the data, the ultimate bond stress mean of all the #4 (13 mm) reinforcing bar was 2,116 psi (14.6 MPa), while the #7 (22 mm) reinforcing bar data had a mean of 981 psi (6.8 MPa). Because the mean ultimate bond stresses were significantly different for the two sizes of reinforcement, the data distribution was bimodal, or had two separate humps. The data distribution was also fairly symmetric.

Dunnett's t-Test compares a set of means against a control group mean. The test reports the absolute value of the difference between the control group and group of interest minus the Least Significant Difference (LSD). The LSD is the difference that is the limit for the difference to be considered significant. If a value is positive, its mean is more than the LSD apart from the control group mean so that group's mean is significantly different than the control group mean. The Dunnett's t-Test is used to compare the ultimate bond stress means instead of a simple percent difference because a statistical analysis will account for the effect of the number of tests and the standard deviation of the data. The confidence level chosen for this test was $\alpha$ = 0.05. After the initial testing phase, a level of $\alpha$ = 0.10 was also used to show a more inclusive set of results. Table 3 shows the results of the Dunnett's t-Test. At a level of 0.05, three tests out of 24 were found to be significantly different from the respective controls. Two of these were the #4 (13 mm) epoxy coated reinforcing bar, 4,000-psi (28 MPa) concrete specimens with form oil and bond breaker as the contaminant. The third was the form oil contaminated #4 (13 mm) 7,000-psi (48 MPa) test specimens.

With the confidence interval of $\alpha$ = 0.10, three tests (in addition to the previous three from the $\alpha$ = 0.05 test) were identified as significantly different. One was the bond breaker contaminated #4 (13 mm) bar 4,000-psi (28 MPa) test specimen. The other two were the #4 (13 mm) 7,000-psi (48 MPa) form oil and bond breaker test specimens. While these three tests are considered significantly different, this must be tempered with the fact that this confidence level is higher than what is usually used in analysis.

A comparison of just the means of the control specimens by Dunnett's t-Test showed that the following were significantly different at the 0.05 level: bar size (uncoated) and bar size (coated). A Least Squares Model analysis verified the significance.

In Table 3, the significantly different treatments are the #4 (13 mm) bar, epoxy coated, 4,000 psi (27.6 MPa) and 7,000 psi (48 MPa), and #4 uncoated at 7,000 psi (48 MPa) tests contaminated with form oil and bond breaker. This trend shows a possible interaction of the form oil and bond breaker contaminants with the smaller bar size, weaker concrete and epoxy bar coating. A Least Squares Model was used to investigate the significance of those interactions. With a confidence interval of 0.05, the interaction of the form oil contaminant with bar size, concrete strength level and coating condition was significant.

## EXPERIMENTAL AND ANALYTICAL OBSERVATIONS

Several observations were made during this test program. Some of them are as follows:

- The majority of beams failed in bond splitting; the remaining specimens failed in bond pullout. The bond pullout occurred primarily in #4 epoxy coated bars.
- The #7 reinforcing bar gives a lower bond stress than the #4 bars for the same embedment length.
- On the macroscopic level, Fig. 6 shows the ultimate bond stresses are of the same magnitude within a given bar size.
- The wedging action caused by the reinforcing bar lugs is thought to have produced the compacted powder on the lugs, previously described by several investigators, notably Park and Paulay (7). As the bond fails, the concrete is compacted into a powder by the lugs, which collects on the lug faces. Fig. 9 shows the compacted powder on the reinforcing bar lugs of an epoxy coated #7 (22 mm) bar.
- From Table 3, of the three cases that differences in means were considered significant at the 0.05 level, it appears as the reinforcing bar size decreases and the surface condition changes to epoxy coated and the concrete strength is reduced, the ultimate bond strength is more likely to be affected by form oil and bond breaker contaminants. This trend was seen as the most likely to affect the ultimate bond strength since a lower concrete strength and epoxy coating weaken the bond stress while acting independently of each other. The concrete splatter tested does not seem to affect the ultimate bond strength at either confidence level.

## CONCLUSIONS

The following conclusions are drawn from the experimental and statistical studies of this investigation:

1. In 13 out of 16 situations tested at $\alpha = 0.05$, a comparison of the means analysis showed that the ultimate bond stress was not significantly affected by the form oil or bond breaker contaminants. None of the situations were significantly affected by the concrete splatter.
2. Two types of failure mechanisms were observed in this study, bond pullout and bond splitting. Most of the failures were by bond splitting, which is attributed to a bearing of the concrete against the lugs of the reinforcing bar, resulting in the splitting of the concrete. The amount of slip associated with this failure is considerably less than observed in a bond pullout failure. The pullout failure occurred with a few of the #4 (13mm) epoxy coated reinforcing bars.
3. As the bar size and concrete strength decrease and the surface is epoxy coated, the specimens appear to be more susceptible to a loss of bond strength caused by bond breaker and form oil contaminants.

## FUTURE RESEARCH

One purpose of this research was to provide a credible basis for future research to be performed with the goal of eventually gathering enough data for the development of appropriate specifications that consider altering the current requirements of cleaning contaminated steel reinforcing bar prior to placement of concrete. Studies that focus on other types of contaminants, setting times, amount of contaminant coverage, reliability studies or factors of safety should be undertaken.

## ACKNOWLEDGMENTS

For their help with funding, the authors wish to thank the University Transportation Center at UMR, McCarthy Construction, Associated General Contractors, Site Advancement Foundation, Industry Advancement Fund, Southern Illinois Construction Advancement Program, St. Louis Construction Training and Advancement Foundation, and the Erectors and Riggers Association of St. Louis.

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