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Effect of manufacturing process and rusting on the bond behavior of deformed bars in concrete

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Abstract

The paper presents the results of an experimental program to assess the effects of manufacturing process and rusting due to extended periods of site exposure on the bond behavior of deformed bars in concrete of ordinary strength. The specimens are exposed to seven exposure periods (0, 3, 6, 12, 18, 24 and 36 months) in the severe environment of the Arabian Gulf. A total of 63 pullout tests covering bars with three different geometries and two manufacturing processes are conducted. For each test, the bond stress vs. slip is recorded until failure. Test results have shown that bond performance of the bars is improved by short exposure; however, an extended exposure tends to adversely affect the bond performance. The decrease in bond strength after 36 months of site exposure is found to be about 10% of that of fresh bars. The manufacturing process has significant impact on the mass loss vs. exposure duration with the quenching process showing superior performance compared to the hot-rolled process. However, this is not reflected in the bond performance of bars from the two processes as they showed similar bond behavior irrespective of the manufacturing process.

Keywords: Rust; Bond slip; Bond stress; Reinforcement; Concrete; Quenching process; Hot-rolling process; Arabian Gulf

1. Introduction

The bond between concrete and the embedded reinforcing steel is essential for the composite action in reinforced concrete construction. For deformed bars, bond depends primarily on the mechanical interlocking between concrete and bar lugs or deformations. This mechanical interlocking is affected by the steel bar profile, bar size, bar surface conditions, concrete cover, and concrete quality [1]. Exposure of the bars to the atmosphere may cause rusting of the bar surface. The extent of rusting depends on the environmental conditions and the period of exposure to the environment. Rusting of bars is a sensitive issue as it is commonly a source of dispute and may result in rejection of steel based only on appearance. Relevant specifications dealing with reinforcing steel have set some rules to minimize this dispute [2–4]. However, the issue is still the subject of controversy among producers, users and the supervising engineers.

Various aspects of bond performance of deformed bars in concrete were investigated by many researchers [5–10]. The effect of rusting on the bond of deformed reinforcing bars in concrete was investigated by Kemp et al. [11] considering various exposure environments. The bond characteristics of deformed bars with deformation meeting ASTM A305 specification were found to be not adversely affected by varying degrees or types of surface rusting. The deformation dimensions were found to be the major parameter governing bond characteristics even for rusted bars. Auyeung et al. [12] considered an accelerated corrosion using an external current source. It was observed that low level of corrosion (<1% mass loss) improved bond strength. When mass loss exceeds 2%, considerable reduction in the bond strength occurred; nevertheless, a measurable retention of bond strength was maintained even after excessive corrosion (6% mass loss). Stanish et al. [13] investigated experimentally the effects of corrosion products on bond strength. Corroded reinforcement was tested for bond strength in tension zones of flexural elements. The results illustrated that bond resistance was adversely affected by the accumulation of corrosion products. Kayali and

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Yeomans [14] studied the effects of surface treatments of deformed bars on the bond strength. Epoxy coating was found to cause significant reduction in bond strength (>20%) compared to black bars while no adverse affect on bond was observed when galvanized steel was used.

Another parameter which may impact the bond behavior is the manufacturing process. Traditionally, steel bars are produced through conventional hot-rolling process in which the heated billets pass through a series of forming operation where the billet cross-section is gradually reduced till the required shape and dimension are achieved. Recently, quenched bars have been introduced to the market. These quenched bars are also produced through hot-rolling; however, they are rapidly water cooled after the last forming operation. The rapid water cooling, called quenching, causes micro structural changes in the bar enhancing some properties of the product including corrosion resistance [15]. The bars produced by the two processes are known to rust when exposed to the open atmosphere with quenching process resulting in faster rusting (discoloring), however, the long-term mass loss of the quenched bars is less than hot-rolled bars. This performance is clearly shown in Fig. 1, which is reproduced from the data by Mehmood et al. [15]. The impact of the manufacturing process and rusting due to atmospheric exposure on the bond performance of bars in concrete has not been adequately addressed in the literature.

This investigation is designed to assess the bond behavior of hot-rolled and quenched bars when exposed to extended periods of site exposure. The bars used have three different geometries designated here as types H1 and H2 from hot-rolling process and Q from quenching process. The geometries of the three types of bars are shown in Fig. 2. The exposure condition was in the open atmosphere in the severe environment of the Arabian Gulf. The conventional pullout bond test according to ASTM C234 [16] was used. The stress vs. slip relationships were recorded and the strength at 0.25 mm slip and at failure were determined. The experimental program and the bond behavior at varying periods of site exposure up to 36 months are presented and discussed herein.

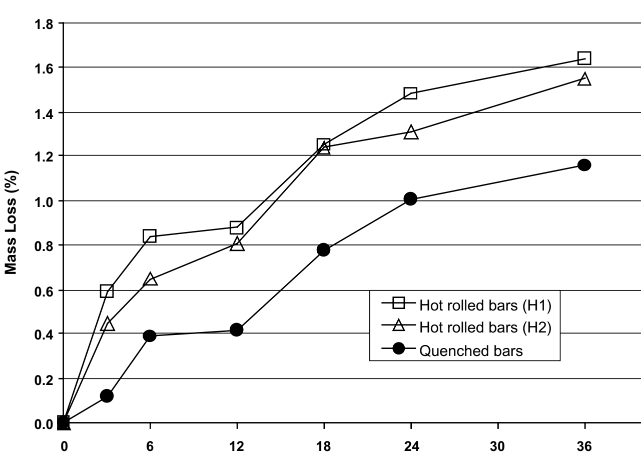

Fig. 1. Mass loss of hot-rolled and quenched bars after atmospheric exposure.

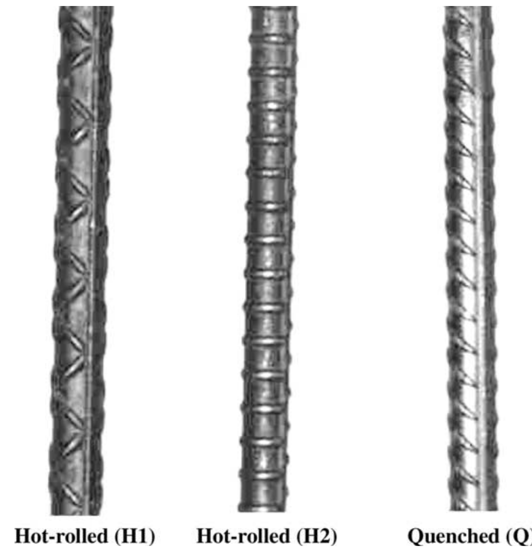

Fig. 2. Geometries of deformed bars.

2. Experimental program

2.1. Materials

The concrete for all specimens was of ordinary strength. It was made from Type I ordinary Portland cement, crushed sand, and a blend of 20 and 10 mm size coarse aggregates. Potable water was used for mixing water. The mix proportions used for making concrete are given in Table 1.

2.2. Specimens and casting procedure

Pullout bond test was carried out using 150 mm cubic specimens with the bar centrally embedded. Steel bars with 14 mm in diameter were used instead of no. 6 (19 mm) bars specified in ASTM C 234 [16] which is used as the basis of casting and testing procedures. Each mould was designed to cast two 150 mm cubic specimens back to back as shown in Fig. 3. The base and the ends were

Table 1
Mix proportions per cubic meter of concrete

Material	Quantity, kg/m^3
Cement	350
Water (free)	210
20 mm aggregate	730
10 mm aggregate	390
Sand	715

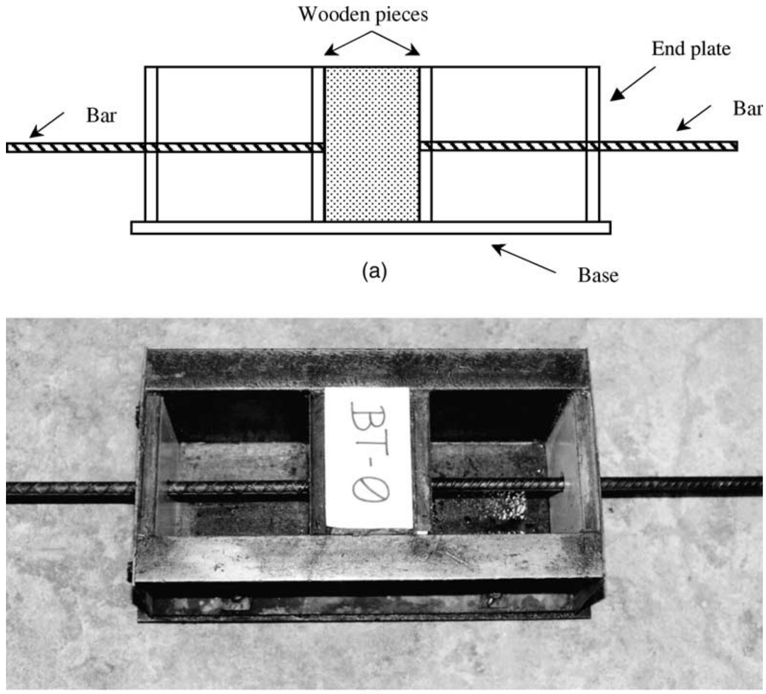

Fig. 3. (a) Vertical section of mould for casting two bond specimens. (b) Photograph of the mold used with the bars in place.

made of steel plates while the sides consisted of steel channels. The bearing surface of each specimen was cast against the end plates and the bottom was molded against 10 mm thick wooden pieces. Both the end plates and the wooden pieces contained central holes to support the bar in the horizontal level.

Seven castings were made using bars covering exposure periods of 0, 3, 6, 12, 18, 24, 36 months. In each casting, nine bond test specimens and six 150×300 mm control cylinders for determining compressive strength were cast. The nine bars used in each casting were of the same exposure times and subdivided into three sets of different geometries. For each bar geometry, three replicates were made.

Mixing was done in a stationary mixer and in accordance with ASTM C192 procedure [16]. When casting the 150 mm cubic bond specimens, concrete was placed in two layers of approximately equal thicknesses and each layer was rodded 25 times. The control cylinders for compressive strength were cast and cured in accordance with ASTM C39 [16]. After casting, the bond specimens were covered with wet burlap and polyethylene sheets and left in the laboratory atmosphere.

The bond specimens were demoulded carefully after 24 h and designated to indicate: test—bar type—exposure time—the replicate number/total replicates. For example, BT-H1-3-1/3 designates a bond test specimen having H1 type bar with exposure time of 3 months and is 1 of 3 identical specimens. After designation, the specimens were placed in lime-saturated water tanks until the testing date. The bars projecting out of the bond specimens were wrapped with PVC insulation tapes before placing them in water. Bond testing was done for all specimens at the age of 28 days.

2.3. Testing details

After the prescribed period of curing, the bond test specimens were taken out of the curing tank and kept moist by wet burlap. Testing was carried out in the moist condition. Out of the six standard cylinders cast, three cylinders were tested for the 7-day compressive strength and the remaining three for the 28-day compressive strength.

A summary of slump measurements and compressive strength results at 7 and 28 days is given in Table 2. The variations in the results are minimized as the preparations of concrete and castings were carried out in the laboratory using identical procedures. For all castings, concrete temperature was in the range of 21 ± 4 °C. Slump measured was in the range of 135–50 mm and the 28-day average compressive strength was in the range of 24.4–8.7 MPa with an average value of 26.5 MPa.

The bond test frame with the specimen in position is shown in Fig. 4. The test frame consisted of two 350 mm square plates each of 24 mm thick connected by four steel bars each of 25 mm diameter. The steel bars were threaded and thereby the distance between the plates could be adjusted. The top plate carried a slot of 35×20

Table 2
Summary of casting data and compressive strength results

Exposure time of bars	Slump, mm	Temperature, °C		Compressive strength, MPa	
		Laboratory	Concrete	7-day	28-day
Fresh	140	22	19	17.3	25.8
3 Months	145	20	17	18.2	28.7
6 Months	135	22	19	17.2	27.2
12 Months	140	22	21	16.6	26.9
18 Months	150	21	23	18.9	24.7
24 Months	150	24	25	17.3	24.4
36 Months	135	21	21	18.3	27.5

mm to accommodate the reinforcing bar and LVDT's. LVDTs were held 100 mm apart using LVDTs holder with a central hole for bar. The distance between the bearing face of the cube and the point on the bar where the holder was attached was maintained at 70 mm.

The specimen was mounted in the frame with the bar passing through the slot in the bearing plate and the LVDT holder was fixed to the bar with the help of two fixing screws. Load was applied to the bar at a rate of approximately 22 kN/min. For each increment of 1 kN load read on the machine, slip was recorded in the computer through HP 3852A data acquisition. Loading was continued until failure.

The load vs. bar slip for the loaded end of the concrete specimens was recorded using two symmetrically placed LVDTs. The average bond stress at each load level, P, was calculated using the following relationship:

$$\mu = \frac{P}{\pi d l} \tag{1}$$

where μ, average bond stress (MPa); d, diameter of the bar ($=14$ mm); l, embedment length ($=150$ mm).

Slip of the bar for each load increment was computed from the average of the two LVDT measurements after correction for the elongation of the portion of the reinforcing bar between the bearing surface of concrete and the point on the bar where the LVDT holder was attached. This was done using the following equation:

$$\Delta_c = \Delta_m - \frac{PL}{A_b E} \tag{2}$$

where Δ_c, the corrected slip in mm; P, the load level in Newton; Δ_m, measured displacement at the load level P; L, distance between bearing face of cube and point on bar where LVDT holder is attached ($=70$ mm); A_b, area

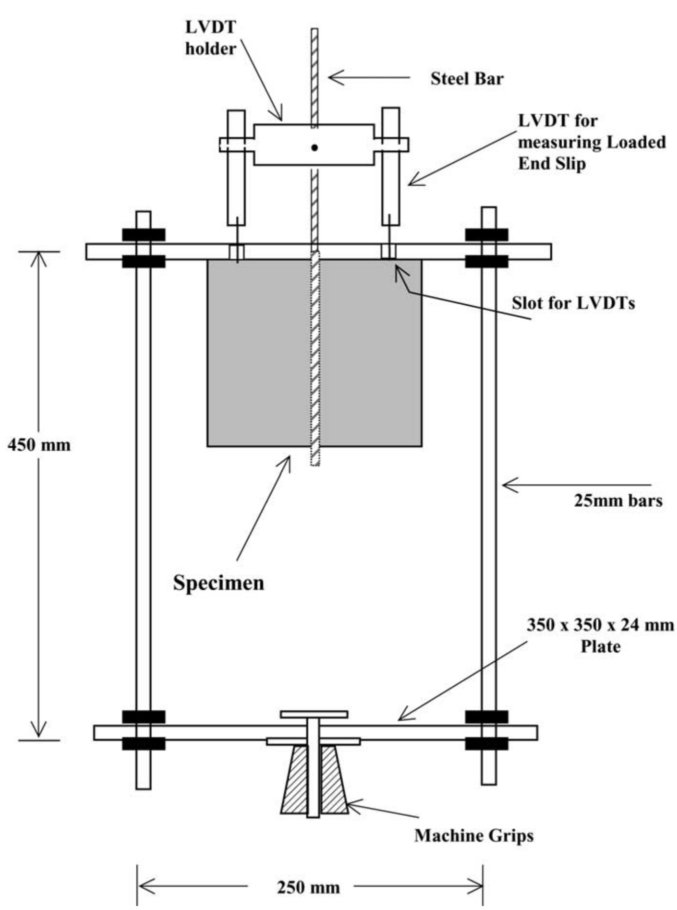

Fig. 4. Bond test setup.

of the bar ($=154$ mm^2); E, modulus of elasticity of bar ($=200$ GPa).

3. Test results and discussions

3.1. Bond stress–slip behavior

The bond stress vs. slip measurements were obtained using Eqs. (1) and (2) for each test specimen. Typical bond–slip behavior of fresh bars is shown in Fig. 5. The behavior is characterized by two regions which is consistent with the findings by other researchers [10]. In region I, the behavior of fresh bars is stiff until a stress level of 3 MPa is reached. In region II, the stiffness is reduced substantially until the slip at failure, which is approximately 0.6 mm, is reached. The reduction of stiffness beyond 3 MPa stress is due to increased slippage associated with loss of adhesion between concrete and steel and possibly due to the formation of microcracks in that zone.

The effects of site exposure, bar geometry and manufacturing process on the bond–slip behavior can be depicted by the typical curves shown in Figs. 6–8. In these figures, the bond–slip relationships for fresh and rusted bars with 12 and 36 months of site exposures are compared. The three figures show consistent trends of behavior. The stress–slip relationship starts stiff in region I and then shows decreased stiffness in region II, irrespective of the exposure time. The effect of rusting on the bond–slip behavior appears to be on the transition between regions I and II. Limited rusting (12 months exposure) improves the bond–slip behavior as it shifts upward the boundary between regions I and II. However, this improvement was not maintained by specimens subjected to more rusting (36 month's exposure). It should be noted that Type H2 bars exhibited smooth transition between regions I and II regardless of the rust conditions. This may be attributed to the deformation characteristics of the bars.

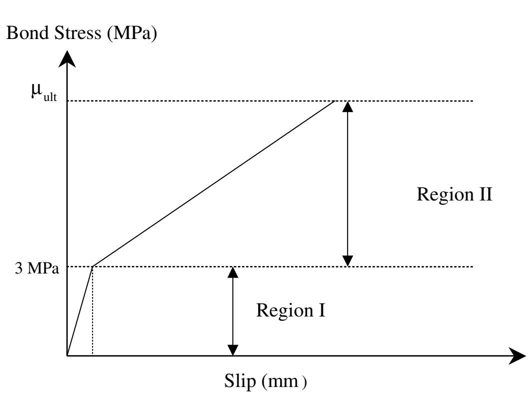

Fig. 5. Typical bond–slip behavior of fresh bars.

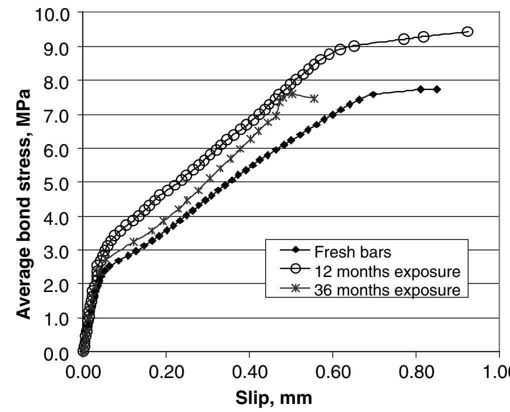

Fig. 6. Bond stress vs. slip curves for hot-rolled bars (H1) after various exposure periods.

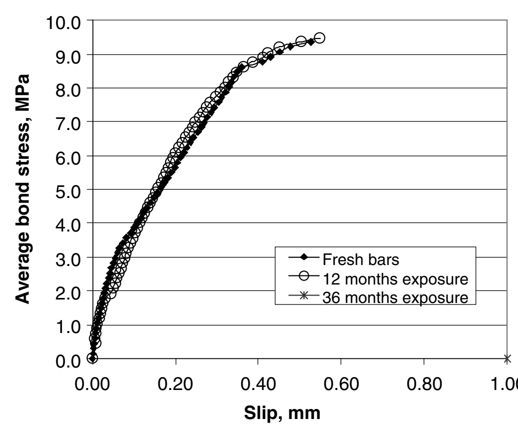

Fig. 7. Bond stress vs. slip curves for hot-rolled bars (H2) after various exposure periods.

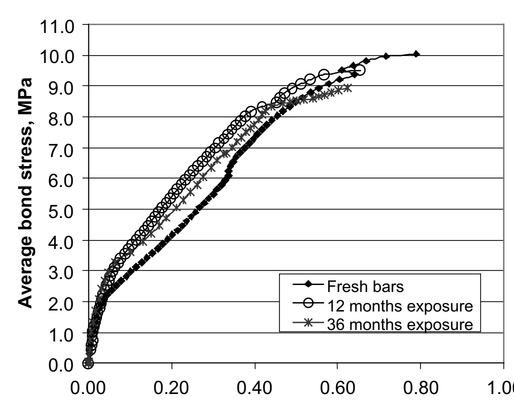

Fig. 8. Bond stress vs. slip curves for quenched bars (Q) after various exposure periods.

3.2. Bond strength

The modes of failure for specimens were similar as all of them failed by splitting of enclosing concrete. As a result of concrete splitting, the specimens broke into two or three pieces with cracks emanating from bar. The average bond strength at failure was computed using Eq. (1) with the load P being the maximum load at failure. The bond strength at 0.25 mm slip was obtained from the bond stress vs. slip relationships. The average bond strengths vs. exposure time are shown graphically in Figs. 9–11 for types H1, H2, and Q, respectively. The three figures show that both the bond stresses corresponding to 0.25 mm slip and ultimate load are reduced with increased exposure time. The trends from the three figures are very similar indicating that the type of bar has no significant impact on the bond–rust behavior. However, the bond stresses corresponding to 0.25 mm slip and the ultimate load of types H1 and Q bars showed more scatter as compared to type H2. This is clearly related to the profile and deformation characteristics of the bars. These characteristics are believed to affect the homogeneity of the bond making the bond strength of some bar geometries more sensitive to the surface condition of the bar than the others.

The effect of the bar type is further elaborated on in Fig. 12. In this figure, the average ultimate bond strengths as percentages of the ultimate strengths of the fresh bars are plotted against the mass loss corresponding to each period of exposure for the three bar geometries. The bond strength used in this figure is normalized to account for the effect of variation in the

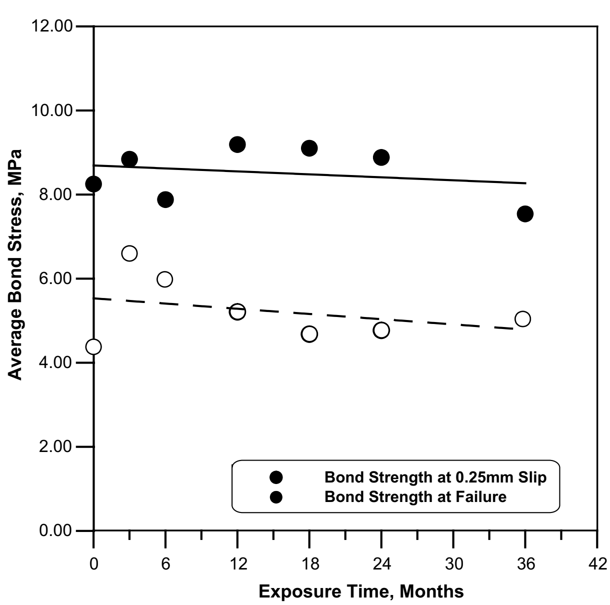

Fig. 9. Average bond strength vs. exposure time for hot-rolled bars (H1).

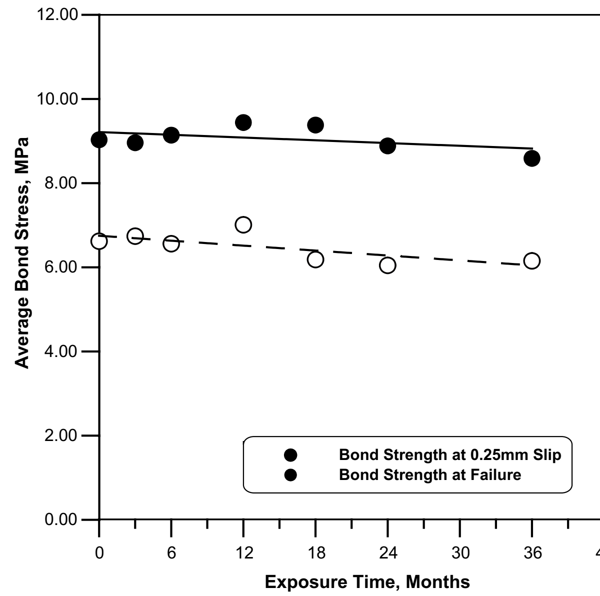

Fig. 10. Average bond strength vs. exposure time for hot-rolled bars (H2).

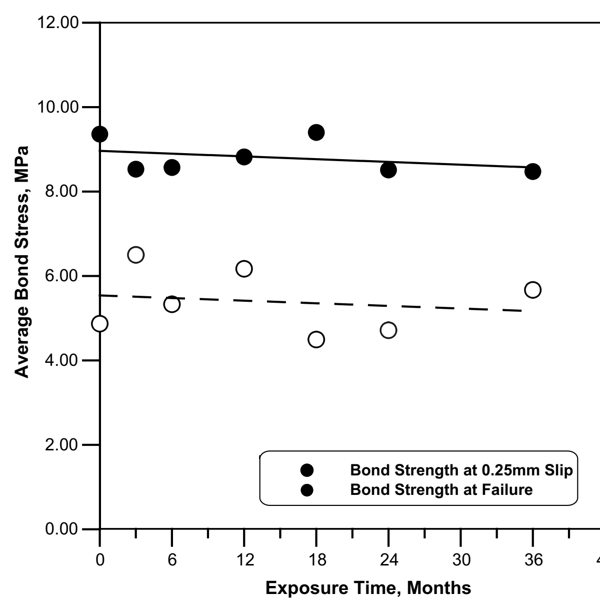

Fig. 11. Average bond strength vs. exposure time for quenched bars (Q).

compressive strength on bond strength using the following equation:

$$\mu_N = \mu \frac{\sqrt{\bar{f}'_c}}{\sqrt{f'_c}} \tag{3}$$

where μ_N, normalized bond strength; $\bar{f}'_c$, average compressive strength of specimens from all castings; and f'_c, compressive strength of specimens from each casting.

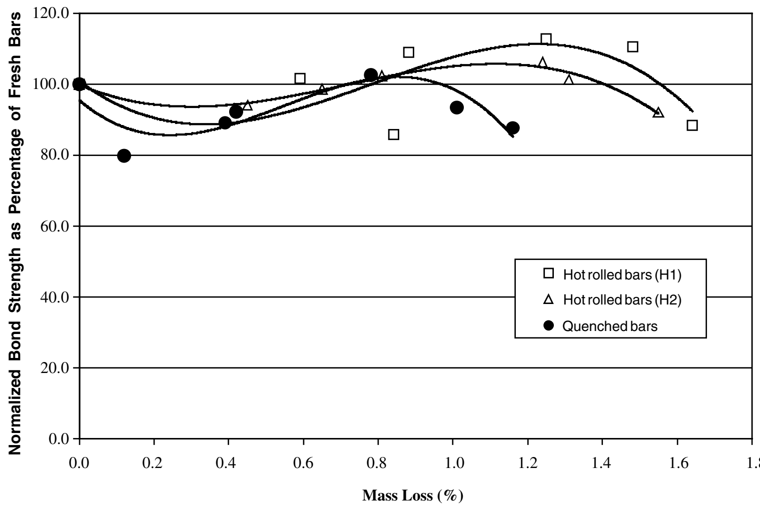

Fig. 12. Ultimate bond strength vs. mass loss for the three types of bars.

The following observations are clearly evident from this figure:

1. The ultimate bond strengths showed consistent trends for all the three bar types used. Three different stages of behavior were observed. Initially, the strength decreased slightly then a gradual improvement was observed followed by a rapid loss of strength. This behavior is attributed to the effect of the different levels of rusting on bond strength. The improvement of bond strength observed in the second stage can be attributed to increased friction resulting from increased roughness of the bar surface due to limited rusting. However, once the rust exceeds certain limit it reduces bond strength as it forms a soft layer reducing both friction and adhesion between concrete and bar surface [9,12].
2. The type of manufacturing process was found to affect the mass loss vs. exposure time characteristics where more loss of mass was observed for the quenched bars (Fig. 1). However, this observation does not seem to have an impact on the bond behavior as shown by the almost identical final strength reduction of about 10% exhibited by all types of bars.

4. Summary and conclusions

An experimental program to assess the effects of manufacturing process and rusting on the bond behavior of deformed bars was conducted. Steel bars of 14 mm in diameters were used. Rusting was generated by exposing the bars to the atmosphere of the severe environment of the Arabian Gulf for periods of 0, 3, 6, 12, 18, 24 and 36 months. The manufacturing processes were the conventional hot-rolling process and the more recent quenching process. Pull-out bond tests were done on unconfined concrete specimens in accordance with ASTM C234. The bond stress vs. slip was recorded for each test until failure. Average bond strength was calculated at 0.25 mm slip and at failure. Based on the results of this investigation, the following conclusions can be made:

1. The bond–slip behavior of bars is characterized by two regions; region I of high stiffness and region II of a substantially reduced stiffness. This was observed for all bars irrespective of the manufacturing process and the rusting extent.
2. Limited rusting tends to improve the bond–slip behavior as it shifts upward the boundary between regions I and II. However, more rusting due to extended site exposure beyond 12 months adversely affects the bond strength at failure. A reduction of 10% was observed after 36 months of site exposure.
3. The manufacturing process has a significant impact on the mass loss vs. exposure duration with the quenching process showing superior performance compared to the hot-rolled process. Yet this was not reflected in the bond performance of bars from the two processes as they showed similar bond behavior irrespective of the manufacturing process.

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