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COATING DISBONDMENT IN EPOXY-COATED REINFORCING STEEL IN CONCRETE — FIELD OBSERVATIONS

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ABSTRACT

A summary on the disbondment of epoxy coating on reinforcing steel extracted from marine substructures in Florida is presented. The bridges examined in this study had been in service for periods ranging from 3 to 13 years. Disbondment was consistently observed in rebar in bridges older than 4 years. The disbondment developed even in the absence of significant chloride ion contamination of the concrete surrounding the rebar. Continued loss of adhesion was observed in most of the specimens even after prolonged storage (1 month to years) in a desiccator. Contamination of the epoxy-steel interface was modest to very small, and the extent of contamination did not show any distinct correlation with loss of bond.

Keywords: bridges, disbondment, epoxy-coated rebar, marine substructures, reinforced concrete

INTRODUCTION

This paper summarizes the FDOT-USF experience with coating disbondment of epoxy-coated rebar (ECR) extracted from bridge substructures. The ECR investigated was from actual production stock, manufactured between 1979 and 1989. While some new variations of rebar coatings are being presently made and beginning to be put in service, a very large inventory of structures (on the order of 100,000) have been built or rehabilitated in the U.S. and Canada with ECR manufactured using methods in force during the period mentioned above. There are no indications that the material examined in this investigation was not generally representative of the rebar used elsewhere during the same period.

Attention to the problem of ECR corrosion developed first in 1986 with the detection of a corrosion spall at the then 6-year old Long Key bridge in the Florida Keys. Numerous additional spalls developed in subsequent years in that and other bridges built with ECR in the same geographical area [1-4]. By 1995, over 300 ECR corrosion related-spalls are affecting 5 major bridges along U.S. 1 in the Florida Keys.

Examination of the ECR in the concrete spall regions showed that the epoxy coating itself was not visibly different from its condition prior to placement in concrete, but that significant corrosion of the steel had occurred beneath the coating. The coating could be easily separated by peeling it away from the corroding metal. The metal corrosion did not affect all the steel in the spall area. Some portions of the steel were bright or only slightly darkened underneath the coating, but the coating could still be easily peeled off the metal. Examination of ECR extracted from surrounding regions of the substructure where no corrosion had developed showed nevertheless that significant loss of coating adhesion existed there as well. An extensive survey of Florida bridges built using ECR [2-4] showed that loss of coating adhesion to visibly uncorroded metal was widespread, independent of the amount of chloride contamination of the surrounding concrete.

Two modes of coating disbondment were therefore observed, the first ("A") associated with visible corrosion of the steel and the second ("B") taking place in the absence of conspicuous corrosion. The evidence strongly suggested that mode B is a precursor to the development of corrosion and mode A disbondment, and this sequential development has been proposed as part of the overall mechanism of corrosion of ECR in concrete [1,2]. This paper concerns mode B disbondment.

Mode B may be conceptually divided into submodes BW and BD (see Nomenclature). Mode BW or wet adhesion loss corresponds to the disbondment observed when the coating-metal surface system still retains a significant amount of the moisture prevalent in the concrete environment. Mode BD or dry adhesion loss [5] designates the loss of adhesion still observed after the rebar has been extracted from the concrete and allowed to dry in a desiccator for a period of several days or even years. Direct field observations address of course only submode BW, since field adhesion tests are performed immediately after rebar extraction or on the surface of rebar exposed at the bottom of a concrete core hole.

PROCEDURES

Examination for BW disbondment in the field in Florida substructures has been performed with a field knife test, which consisted simply of using a sharp pocket knife to make a cut on the coating surface and then attempting to introduce the knife blade between the coating and the metal. If the blade could be introduced a few mm, thereby exposing the metal surface with no visible coating residue while peeling off a visibly whole portion of coating, the coating was deemed to be disbonded in the BW mode and rated Y (yes). The rating was P (partial) if only a portion of the coating adjacent to the cut could be separated, and N (not) if the knife could not penetrate beyond the cut without breaking the coating into small shavings.

Examination for BD disbondment was performed in the laboratory with field-extracted samples that were placed in a glass desiccator with calcium sulfate dessicant (replaced as needed to keep a blue indicator color) for periods that ranged from one month to over 2 years. Two types of tests were performed. The first was a laboratory knife test, which is described next in some detail as experience has shown that careless procedure may fail to detect otherwise pronounced BD disbondment.

The laboratory knife test began by locating a portion of the rebar segment surface between deformation ribs and making three short intersecting cuts delineating a small triangle, with sides a few mm long. The knife had a sharp pointed blade, replaced often. Careful attention was directed to ensuring that the cuts penetrated all the way to the metal surface, leaving a line of clearly exposed bright metal at the bottom of the cut. An attempt was then made to introduce the tip of the sharp knife between the coating and the underlying metal, observing closely (with the aid of a magnifying glass) to ensure that the blade did not become jammed against metal burrs or other irregularities. The results of the test could grouped into four disbondment rating categories. Disbondment rating 0 was assigned when the knife induced only cohesive coating failure, so that no coating could be removed without breaking the coating into small shavings. This condition is similar to that typically encountered in as-manufactured ECR that has not been put in service and has not suffered mechanical damage due to bending. Disbondment rating 1 corresponded to a mostly cohesive failure, but with a few zones of clean coating separation from the metal surface. Disbondment rating 2 corresponded to mostly adhesive failure, with a large fraction of the coating peeled off the metal surface as a continuous sheet. Disbondment rating 3 was assigned when the coating could be pried off as an essentially continuous triangle with no visible epoxy left adhering to the base metal.

The second type of test for BD disbondment used a mechanical pulloff device. A carbon steel dolly with a diameter of 6.3 mm, machined to a curvature fitting the side surface (between deformation ribs) of the ECR specimen was prepared for use in most specimens. Smaller dolly sizes (down to 4.8 mm) were used for specimens with small inter-rib spacing. The dolly was attached by means of a cyanoacrylate adhesive after the ECR surface was previously locally prepared by light sandpapering and degreasing with acetone. After the adhesive set, the epoxy coating on the perimeter of the dolly was removed with a rotating dental drill bit. The dolly was then pulled using a universal joint fixture that minimized off-center loading. The pull load was increased slowly to achieve pulloff typically one minute following the beginning of load application. The pulloff force was recorded and divided by the dolly area to obtain a pulloff strength. The epoxy coating was not always separated from the base metal in the entire region beneath the area of contact with the dolly. The fraction of the dolly contact surface that corresponded to actual coating separation from the base metal was recorded; the rest corresponded to failure of the epoxy-cyanoacrylate-dolly metal bond.

The coating backside surface exposed in the BD mode disbondment tests was also examined visually and with the aid of an ≈50X microscope. The backside surface typically showed black or gray dots covering a small percentage of the surface, and occasionally dispersed rust discoloration on a portion of the remaining surface. Sometimes bright metal particles were visible, attributable to steel shavings created during the triangle cutting procedure. Tests with copper sulfate solution in selected specimens were used to identify this loose metal presence. The loose metal particles were not counted as part of the contamination. A visual estimate of the percentage of the surface covered by black dots and red discoloration was made (aided by contrasting with a pictorial reference guide [6]) for each specimen that had a BD rating 1 or greater, or that experienced coating-base metal separation in a pullout test. Each specimen was evaluated by two independent operators and the results averaged.

RESULTS AND DISCUSSION

Over 30 bridges in the FDOT inventory (including some plain steel rebar controls) have been examined recently for ECR performance [1,2]. A compilation of the disbondment findings of that investigation is presented here along with additional analysis. Table 1 summarizes the field observations and selected bridge information for the 26 ECR structures in the previous study plus two additional ECR bridges examined in a separate survey. The three-character Bridge Name identifier is keyed to the bridge information given in Refs. [1-2]. The ages of the bridges at the time of examination were between 3 and 13 years. Only two bridges received an N rating for BW adhesion, and both were less than 5 years old at the time of testing. Three other bridges (ages 9 to 12 years) received a P rating, and the remaining 23 structures (ages 3 to 13) received a Y rating. Four structures in the latter group showed also mode A disbondment, as corrosion of the ECR was already in progress. Unless otherwise indicated, the numbers given in Table 1 are averages of the results from the ECR samples examined for each bridge.

Table 1 also shows the highest chloride ion concentration (acid-soluble) measured at a depth of 9 cm among all the cores available from each bridge [1]. The median concrete cover depth of the rebar samples extracted in this investigation was 10 cm. The depth of 9 cm was sampled for chloride routinely, so that the values shown are representative of the highest levels of chloride contamination expected at the rebar position. With the exception of the structures already showing mode A disbondment, the overwhelming majority of the BW disbondment was associated with concrete contamination levels of less than 0.2 kg/m^3, which are typical of background chloride contamination allowable at the time of construction. Table 1 shows also the "% bare area", or extent of coating breaks measured on the surface of the extracted specimens as reported in Ref.[1].

The findings described above indicate that mode BW disbondment was widespread, and already present for the most part before the chloride ion contamination front had reached down to typical rebar cover values. The results suggest also that the disbondment process appeared to have taken about 3 to 5 years to develop.

Figure 1 summarizes the results of the knife disbondment tests on the dried specimens. About three quarters of the specimens still showed pronounced bond loss (BD rating 3) after extended periods of desiccation, while only less than one tenth showed coating adhesion comparable to that of newly produced material (BD rating 0).

Figure 2 (reproduced from Ref.[1]) shows the results of the pulloff tests of BD disbondment in ECR specimens removed from the bridges. Tests were also performed with 2 control ECR specimens that were stored in the laboratory in the as-produced condition and had never been in service. The results are displayed as a cumulative distribution graph. While the pulloff test is limited by the effectiveness of adhesion between the test dolly and the epoxy, the results nevertheless show a distinct reduction of adhesion for the field-exposed rebar group versus the unexposed controls. The adhesion strength between the epoxy and the rebar metal in the control group was always greater that between the test dolly and the epoxy (as evidenced by the consistent failure of the test-dolly-epoxy joint in that group). Thus, the actual effect of field exposure on reducing adhesion is likely to be even greater than the distance between the two distribution curves in Figure 2. The figure shows also the fraction of the pulloff surface that experienced separation between the coating and the base metal (proportional to the extent of dark filling of each data symbol). Full separation was more common for specimens with pulloff strengths below the median. None of the unexposed control specimens experienced any separation between coating and base metal.

Figure 3 shows a summary of the backside contamination visual estimates of the field-extracted specimens (92 specimens). As in any visual estimation technique, the results are semiquantitative; however, some general trends can be gleaned from the results. The median estimated contamination was $\approx$ 10%; and $\approx$ 90% of the specimens exhibited less than 30% estimated contamination. There was no clear correlation between the knife test BD rating (in the 1-3 range) and the estimated percentage of backside contamination, or the puloff strength of the specimens examined. Likewise, examination of the bridge-averaged values in Table 1 shows no discernable correlation between the estimated percentage contamination and the age of the bridge or the extent of bare surface area. The results indicate that backside contamination in most of the specimens was in a range comparable to that expected from present-day voluntary certification programs for ECR production. This, together with the absence of identifiable correlation between observed contamination on the other disbondment indicators, suggests that the disbondment is not attributable to unusual contamination of the bar surface at the time of production. The disbondment was observed on ECR manufactured by several suppliers over a period of one decade, so that other systematic deviations from usual production practice do not appear to have been a likely cause.

The evidence presented here shows that disbondment between the epoxy coating and the metal substrate was a chronic occurrence in the ECR used in the substructure of marine bridges in Florida. The disbondment developed without the need of significant chloride ion contamination of the surrounding concrete, and was observed in all examined structures older than 4 years. The disbondment was observed readily in just-extracted ECR samples as well as in ECR segments exposed in the structure by concrete coring. Examination of the rebar samples after extended periods of desiccator storage showed that the disbondment was permanent in the overwhelming majority of the cases. The permanent bond deterioration was observed by manual knife tests and confirmed with mechanized procedures that were less operator-dependent. The disbondment could not be ascribed to the systematic presence of unusual backside contamination problems or other systematic production deficiency.

These observations document the widespread appearance of deterioration of the epoxy -metal bond of ECR in concrete in warm marine environments. This bond deterioration took place within a time period that is very short compared to the desired length of the initiation stage of corrosion if long-term durability goals (for example 75 years) are sought. Because the deterioration does not seem to be related to obvious production deficiencies, the problem may be inherent to the normal materials properties and/or the procedures used to prepare ECR during the time period in which the structures examined were constructed. Laboratory investigations, conducted with ECR of comparable origin to those extracted in the field have been performed to shed light on the possible mechanism of disbondment and the conditions in which it may develop. Preliminary results of those investigations have been published in recent years [1-4,7], and supplementary findings will be presented in a subsequent paper.

CONCLUSIONS

1. Disbondment between the epoxy coating and the metal substrate was consistently observed in the substructure of marine bridges older than 4 years.

2. The disbondment developed even in the absence of significant chloride ion contamination of the concrete surrounding the rebar.

3. Epoxy-metal substrate adhesion loss was observed in a large majority of the specimens even after long periods of desiccator drying following extraction from the structures.

4. Estimated coating backside contamination levels were very small to moderate in the vast majority of the specimens, and no correlation was evident between loss of adhesion and extent of backside contamination.

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findings, and conclusions expressed here are those of the authors and not necessarily those of the Florida Department of Transportation.

NOMENCLATURE

Disbondment Modes:

Mode A: Present in ECR experiencing visible corrosion of the steel.

Mode B: Disbondment not in the presence of conspicuous corrosion.

Mode BW: "Wet" adhesion loss, observed in rebar freshly extracted from a structure or still in place.

Mode BD: "Dry" adhesion loss, observed in rebar samples kept in a desiccator for extended periods of time.

Disbondment Ranking:

BW: Y (yes); P (partial); N (not disbonded).

BD: 3 (fully adhesive failure of the coating-metal interface).

2 (mostly adhesive failure)

1 (mostly cohesive coating failure, with some coating-metal separation)

0 (cohesive coating failure only)

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TABLE 1
SUMMARY OF OBSERVATIONS

BRIDGE NAME	AGE AT TEST	BW RANK	BD RANK	PULLOUT STRENGTH (PSI)	PULLOUT %	BACKSIDE CONT % ESTIMATE	REBAR SURFACE CORROSION	BARE AREA % ESTIMATE	MAX 9-CM [Cl-] (PCY)
GRN	6	Y	3.0	1804	85	4.8	N	0.22	0.11
7MI	9	Y	3.0	949	100	17.9	Y	2.70	8.8
75N	11	Y	3.0	772	0	12.4	N	0.80	0.24
75S	11	Y	3.0	1384	100	20.3	N	0.05	0.13
HAL	5	Y	2.0	599	50	15.8	N	1.90	0.26
IR1	6	Y	3.0	545	100	12.2	N	0.76	0.63
NWR	10	Y	3.0	315	100	7.6	N	0.90	0.12
VA2	9	Y	2.0	1373	100	14.1	Y	0.43	9.1
VA1	9	Y	3.0	513	90	6.2	N	0.74	7.1
SNK	11	Y	ND	1890	0	4.0	N	5.00	2.5
ITA	3	Y	3.0	854	2	11.3	N	0.03	0.16
ITB	3	N	1.0	1797	85	1.0	N	0.55	0.02
MAT	12	Y	2.5	ND	ND	20.1	N	0.99	0.16
PC1	9	P	3.0	1512	0	20.3	N	3.80	0.17
PC2	12	P	3.0	599	10	8.0	N	1.00	0.2
PC3	12	P	3.0	471	100	9.8	N	2.40	0.23
CHO	13	Y	3.0	ND	ND	35	N	1.00	5.4
PER	11	Y	1.4	ND	ND	26.3	N	2.30	0.36
APA	4	N	0.5	ND	ND	17.7	N	0.03	0.37
IT2	9	Y	3.0	1112	21	16.8	N	0.31	0.76
IT3	9	Y	3.0	426	97	17.6	N	1.20	2.1
NWP	6	Y	2.3	984	0	6.3	N	5.00	2.4
HOB	6	Y	2.3	684	100	4.1	N	0.01	1.4
MI1	8	Y	3.0	513	100	17.1	N	0.24	0.16
MI2	8	Y	2.0	685	100	15.8	N	0.05	0.21
SSK	7	Y	2.5	827	20	14.0	N	0.57	0.37
NIL	8	Y	*	*	*	*	Y	*	7.8
LKY	8	Y	*	*	*	*	Y	*	20

ND: NO DATA
*:NIL AND LKY BRIDGES PARTIAL INFORMATION FROM SEPARATE SURVEY

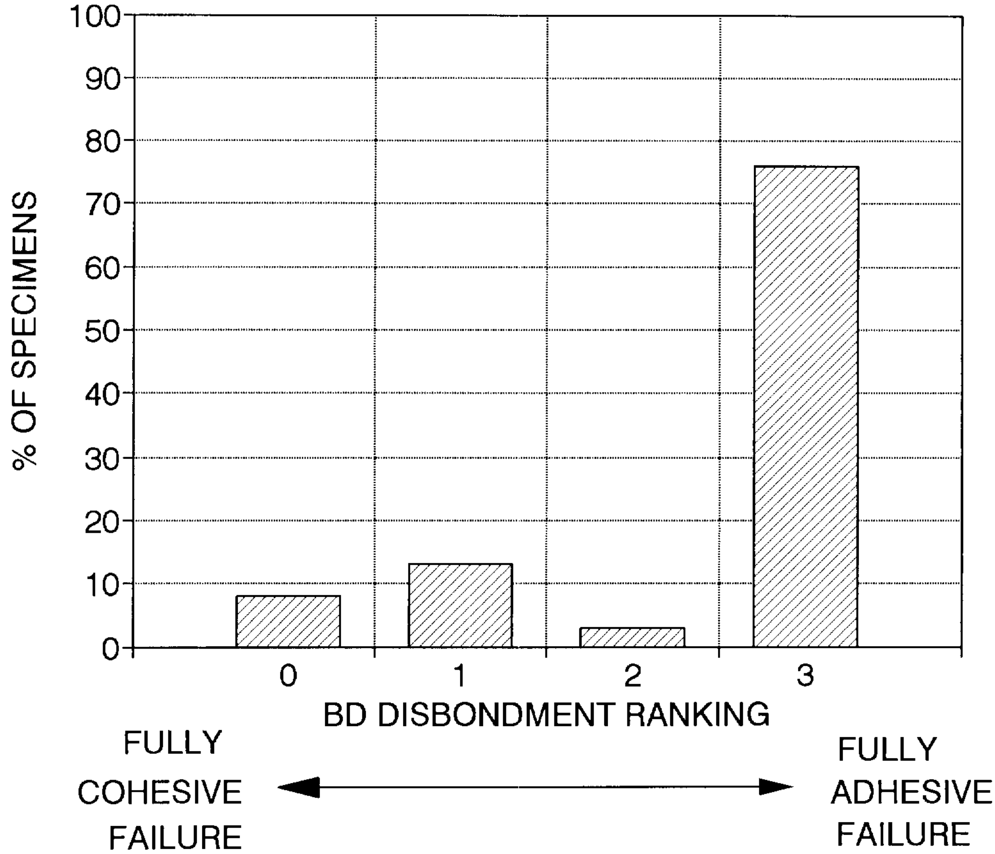

Figure 1. Knife disbondment test results for dry specimens (Mode BD disbondment rating)

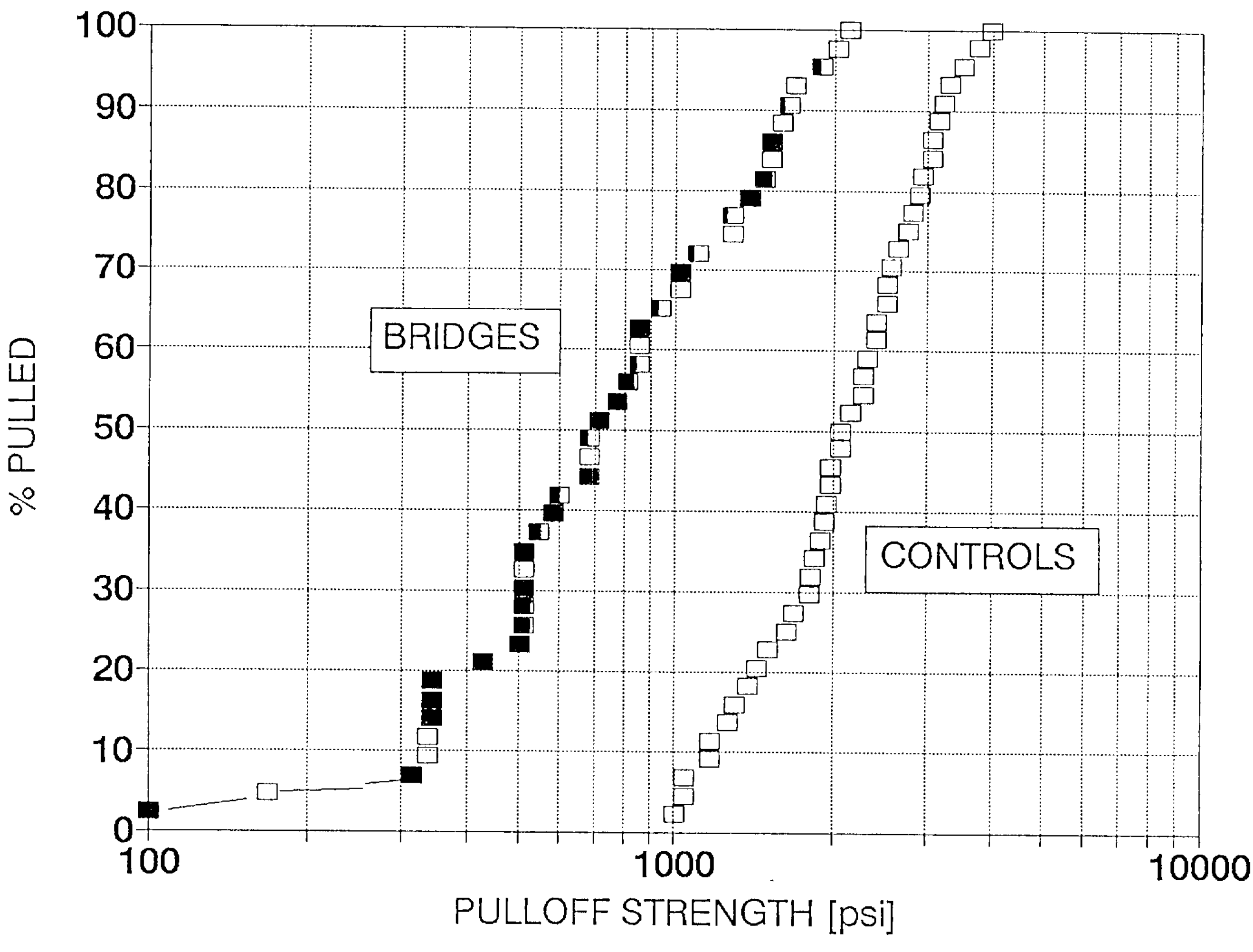

Figure 2. Distribution of the pulloff strength of ECR specimens extracted from the field bridge sites and of unexposed controls (Ref.[2]). Completely filled symbols indicate total epoxy-base metal separation under the test dolly. Partial filling is proportional to fraction separated. (1,000 psi = 6.895 MPa).

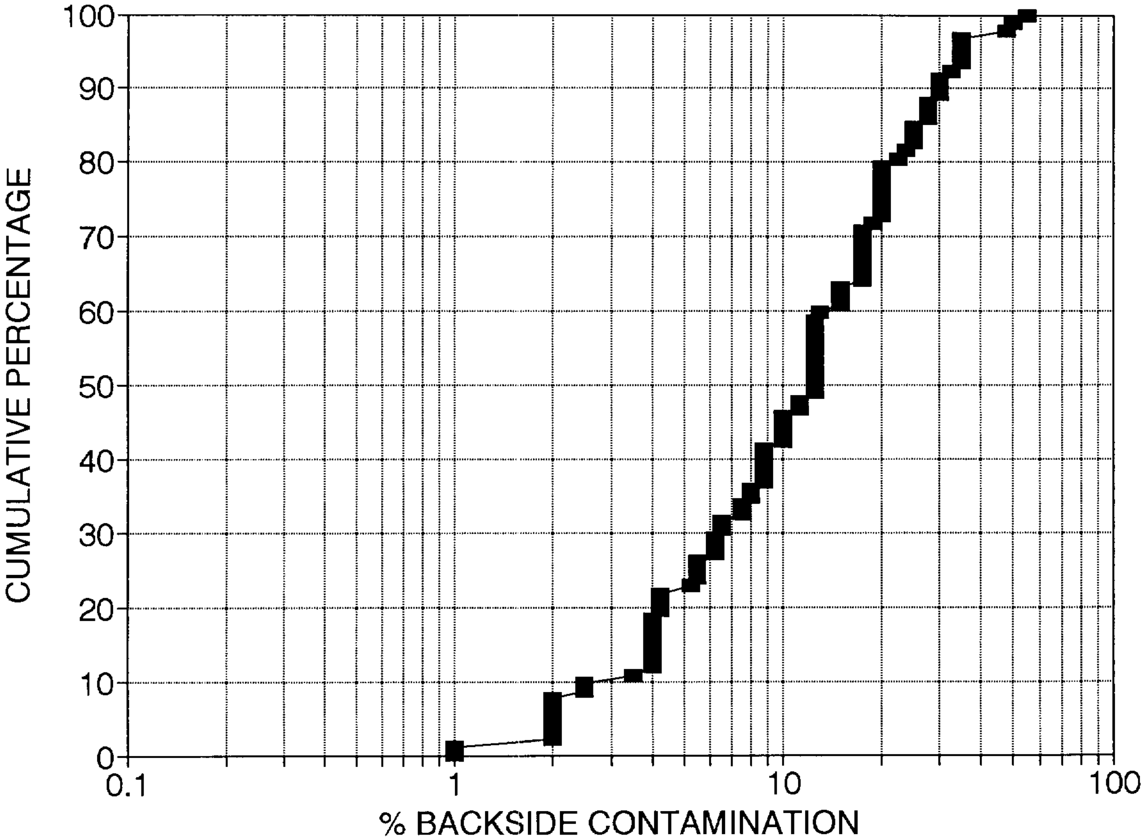

Figure 3. Distribution of the % backside contamination in field-extracted samples with BD rating ≥ 1.