Choices in corrosion-resistant rebar

A comparison of the features, performance, and costs of five rebar options

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Glass-fiber-reinforced-polymer rebar can have twice the tensile strength of steel bars but are only one-fourth the weight. And because they contain no steel, GFRP bars won't corrode.

Because corrosion of reinforcement can result in concrete cracking, staining, spalling, and costly repairs, corrosion-resistant reinforcement often is the obvious choice for concrete structures exposed to high chloride levels. What isn't so clear-cut is the best type of rebar to use for a particular project.

Epoxy-coated, galvanized, glass-fiber-reinforced-polymer, solid stainless-steel, and stainless-steel-clad reinforcing bars all are designed to resist corrosion, especially chloride-ion induced corrosion. Before selecting one of these products for your next job, you should consider such factors as initial cost, construction concerns, degree of corrosion resistance, and long-term performance. The following comparison of the five rebar options can help you make an informed decision.

Epoxy-coated rebar (ECR)

Epoxy coatings on rebar are designed to act as a physical barrier, isolating the steel from the three primary elements needed for corrosion to occur—oxygen, moisture, and chloride ions. The coating also serves as an electrical insulator for the steel and minimizes the flow of corrosion current.

Though bars completely coated with epoxy won't rust, their performance depends on the quality and integrity of the coating. When coating defects, called *holidays,* and damage occur, corrosion resistance decreases. Most damage, such as chips, scraps, and mashed areas, occurs during rebar transportation, handling and placing, and when fresh concrete forcibly strikes the bars.

As with black or uncoated rebar, ECR performance also depends on the extent of concrete cracking, depth of concrete cover, and chloride concentration levels. Coupling coating defects and damage with harsh exposure conditions can lead to premature corrosion and poor ECR performance.

Since the mid-1970s, ECR have been used extensively because it was assumed that the epoxy coating would prevent corrosion problems. However, reports started surfacing in the early '90s about ECR failures, most notably in concrete bridges in the Florida Keys. Responding to these reports, the Federal Highway Administration recommended that states evaluate ECR performance in existing bridge decks. Following are some of the key findings of these evaluations (Ref. 1):

- The overall condition of the ECR structures was good, with only isolated areas of deterioration. Any cracking and delaminations in the bridge decks were not caused by ECR corrosion.
- Of the 202 ECR samples taken from the bridge decks, 81% did not have any corrosion. Areas that did corrode were typically at locations with visible holidays or bare steel. Heavily corroded ECR samples were in areas with shallow concrete cover and high chloride concentrations.
- Average chloride concentrations near the rebar were at or above the threshold level necessary to initiate corrosion in black steel. In areas with inadequate concrete cover, chloride concentration levels usually were higher and the concrete was typically cracked.

In the bridge decks evaluated, nondamaged epoxy coatings provided an adequate barrier system and effective corrosion protection for as long as 20 years, reiterating the importance of handling ECR with care and properly repairing all coating damage (Ref. 2). In addition to the field evaluations, accelerated corrosion research in the laboratory confirms that coating the rebar completely with epoxy is critical to achieving corrosion resistance, espe-

Table 1 Comparison of corrosion-resistant rebar

Type of rebar	Times more corrosion resistant than black rebar	Scratch and chip resistance	Bending	Cutting	Welding	Chloride threshold	Cost, $/lb[1]
Epoxy-coated ■ Damage level 0.5% ■ Damage level 0.004%	 150 to 1,175 69 to 1,762	Easily damaged, requiring field repairs	Allowed but can damage epoxy coating	Allowed; coating of cut end required	Allowed; coating of weld required	 Same as black rebar Very high	0.32
Galvanized (zinc-coated)	38	Very tough; hard to damage	Allowed but may weaken coating	Allowed; coating of cut end required	Allowed; coating of weld required	4 to 10 times higher than black steel	0.50
GFRP	Won't corrode	Fairly tough; difficult to damage	Field bends not allowed	Allowed; sealing of cut end may be required	Nonweldable	Immune to chloride attack	3.00 to 4.00[2]
Solid stainless steel	800 to 1,500	Not an issue	Allowed	Allowed	Allowed; special welding procedures apply	15 to 24 times higher than black rebar	1.60
Stainless-steel-clad	Same as solid stainless-steel rebar	Very tough; nearly impossible to damage	Allowed	Allowed; coating of cut end may be required	Allowed; special welding procedures apply	Same as solid stainless-steel rebar[3]	0.60

[1]Costs shown are based on Reference 5 and information from industry experts. They are material costs only and may vary in different parts of the country.

[2]GFRP density is considerably less than steel and values cannot be directly compared to steel rebar.

[3]Values assumed the same as solid stainless steel.

cially in cracked concrete and where ECR is electrically tied to black steel.

In tests of precracked concrete specimens using black cathodes (with the ECR tied electrically to black steel), the corrosion rates for rebar with coating damage on 0.5% of the surface were 2.1 to 36 times lower than the rates for black steel. For ECR with 0.004% coating damage, values were 6.7 to 289 times lower . In uncracked concrete with an epoxy cathode, corrosion rates of ECR with 0.5% coating damage were 150 to 1,175 times lower than those for black rebar. For ECR with 0.004% coating damage, the rates were 69 to 1,762 times lower (see Table 1). Researchers attributed the wide range of results to the different brands and types of epoxy coatings used in the research.

It's important to note that the chloride threshold to initiate corrosion in ECR with 0.5% coating damage is the same as the threshold level for initiating corrosion in black steel (Ref. 3). For ECR with coating damage of 0.004% or less, the threshold is higher because the epoxy coating prevents chloride ions from coming into contact with the steel. In the field, this means that damage to the epoxy coating resulting from construction could lower chloride threshold limits. Research also indicates that bent bars have lower resistance to corrosion than straight bars because the bending action damages the epoxy coating in the bend area.

Epoxy-coated rebar resist corrosion more effectively if any damage to the coating is repaired.

Galvanized rebar

Hot-dipped galvanized, or zinc-coated, rebar have been used since the 1930s, but reports on their performance are conflicting, especially when the rebar are subjected to high chloride concentrations. One researcher says the threshold level for initiating corrosion is 4 to 10 times higher than the threshold level for black rebar. Other researchers say galvanized rebar will produce only a slight increase in the life of a structure in severe chloride environments (Ref. 4).

The zinc coating protects the steel by acting as a barrier. If the coating is damaged, it self-heals to some extent by forming a nonexpansive, sacrificial corrosion layer that protects the underlying steel. Accelerated corrosion results indicate that galvanized rebar is 38 times more corrosion resistant than black steel for uncracked concrete using a galvanized cathode. For cracked concrete and a black cathode, the corrosion rate increases 41% (Ref. 3). This clearly indicates the need for good-quality, crack-free concrete and no galvanic coupling between coated and uncoated reinforcement. When using galvanized rebar, be sure all the bars and hardware are coated with zinc. Cut ends and welds must be coated with a zinc-rich primer.

Table 2 Cost ratio of black rebar to corrosion-resistant rebar

Rebar type	Ratio
Black (at 24¢/lb)	1.0
Epoxy-coated	1.33
Galvanized	2.08
Solid stainless steel	6.67
Stainless-steel-clad	2.5

Glass-fiber-reinforced-polymer (GFRP) rebar

Composed of resin-impregnated glass fibers and containing no steel, GFRP rebar are immune to chloride and chemical attack. In addition, the bars are nonconductive and have high strength-to-weight ratios. They have a tensile strength as much as twice that of conventional steel reinforcement yet are only one-fourth the weight (a bundle of 10 #6 bars weighs only 75 pounds). Because GFRP rebar are nonconductive, they don't affect magnetic fields and radio frequencies, making the bars ideal reinforcement for concrete in the vicinity of magnetic resonance imaging (MRI) equipment, radio and compass calibration equipment, or high-voltage transformers, cables, and substations.

Since GFRP has different qualities than steel, important design differences and construction considerations exist. For example, the tensile modulus of GFRP reinforcement is only one-fifth that of steel, which may limit span lengths. All bends for GFRP rebar must be made at the factory; field bends are not allowed. Cutting is allowed, but since high-pH materials, such as concrete, will degrade the exposed glass fibers, manufacturers may recommend sealing of the cut ends. Some manufacturers, however, say sealing is not necessary because any degradation that occurs will be minor. GFRP rebar cannot be welded or mechanically spliced.

Solid stainless-steel rebar

Made of a steel alloy formed by the addition of chromium, nickel, and molybdenum, stainless steel is chemically inactive and highly resistant to corrosion because of the thin, chromium-rich oxide layer formed on the steel surface. Adding different amounts of chromium, nickel, and molybdenum creates different grades of stainless steel. For reinforcing steel, Grades 304 and 316 are the most common, with Grade 316 being the most popular. Though researchers report that Grade 316 is slightly more resistant to chloride-induced corrosion than Grade 304, they recommend basing grade selection on physical and design properties since the corrosion resistance of the various grades of stainless steel are so similar (Ref. 5).

Accelerated corrosion testing indicates that stainless steel rebar are 800 to 1,500 times more corrosion resistant than black rebar and have a chloride threshold 15 to 24 times higher (Ref. 3). However, Grade 304 bars may be susceptible to corrosion when used in a severe environment with a black cathode, while Grade 316 bars seem to be unaffected by precracking of the concrete prior to testing and the use of a black cathode. Even in the presence of high chloride concentrations, it appears that stainless steel rebar may last 100 years (Ref. 3).

Stainless steel rebar can be bent, cut, and welded in the field and are very resistant to scratches and chips. Mashed areas, cut ends, and welds do not need to be coated.

Stainless-steel-clad rebar

Reinforcing bars clad in stainless steel have been introduced recently in the United States. A thin outer cladding of stainless steel is bonded to a conventional carbon-steel core, creating a composite rebar that has the same corrosion resistance as solid stainless-steel rebar, according to the manufacturer. The cladding is very tough and nearly impossible to scratch or chip. The cladded rebar can be bent, cut, and welded, though some specifiers may require cut ends to be coated.

Cost comparisons

The costs of epoxy-coated, galvanized, GFRP, and solid and cladded stainless-steel rebar vary nearly as much as the physical and corrosion-resistance properties. Table 2 shows the cost ratio of black steel to four types of corrosion-resistant rebar, based on the cost figures given in Table 1. (Because GFRP is considerably less dense than steel, its cost per pound can't directly be compared to the various steels.) These figures compare only material costs, so to determine in-place costs, you must consider fabrication costs as well.

When comparing rebar options, be sure to look beyond the initial cost and consider the potential long-term benefits and total life-cycle costs. Surveys have shown that using corrosion-resistant rebar may increase the initial cost of a project by only a few percent, which means the bars may prove to be very cost-effective in the long run.

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