

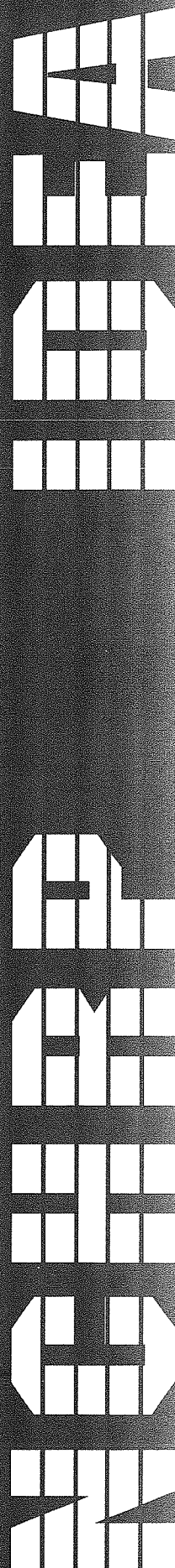
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IDEA *Innovations Deserving
Exploratory Analysis Project*

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM



Report of Investigation



IDEA PROJECT FINAL REPORT

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ALUMINUM BRONZE ALLOY FOR CORROSION-RESISTANT REBAR

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EXECUTIVE SUMMARY

Rebars of three alloys were investigated for resistance to chloride ions at two pH levels. The alloys were aluminum bronze, ductile iron and mild steel. Samples of mild steel rebar were selected from commercial sources. Rebars of aluminum bronze and ductile iron had to be produced by a custom-made process. Aluminum bronze rebar showed excellent corrosion resistance. Both ductile iron and steel had poor corrosion resistance, with ductile iron being somewhat better than mild steel. The mechanical properties of the custom-made aluminum bronze rebar tested lower than the steel rebar. It was demonstrated that an inexpensive cold working process called drawing could increase the mechanical properties of the aluminum bronze alloy. An 18% reduction in area by cold drawing was sufficient to raise the yield strength of aluminum bronze rebar to meet ASTM Specifications for steel rebar.

INTRODUCTION

Significant structural deterioration exists in 40% of the highways in the northeastern United States, as reported in the National Highway Survey of Roads. Other surveys have indicated similar conditions along coastal highways and in bridges and parking garages due to deicing salts. This results from corrosion of the mild steel bar used for reinforcement of concrete. Corrosion reduces load-bearing strength and increases susceptibility to failure. Corrosion of the mild steel rebar is caused by exposure to chloride-ion concentration along with humidity. To solve this problem, researchers are investigating a number of innovative reinforcement materials. They fall into four genres:

- Coating mild steel rebar with an organic coating that in itself is highly resistant to chloride-ion corrosion. Example: epoxy coatings.
- Coating mild steel rebar with metals or alloys that are highly corrosion-resistant. Examples: copper, nickel, stainless steel.
- Replacing mild steel rebar with rebar made from a highly corrosion-resistant metallic alloy. Example: 316 stainless steel.
- Reinforce concrete with high strength filaments that are inert to corrosion. Examples: glass fibers, graphite filaments.

Some of these materials have not been accepted because of lack of uniformity and poor reliability, others because of high unit cost. Specific examples are:

- Epoxy-coated mild steel rebar may have small surface voids, cuts or scratches that allow corrosion penetration; deterioration by aging may limit its usefulness. Careful handling is required in order to not damage the coating. This is extremely difficult to achieve in a construction site.
- Metallic-coated mild steel rebars are similarly prone to nicks and penetration, both during transportation and on the construction site. Areas of surface damage and subsequent corrosion penetration are difficult to detect and repair. The cost of the coating process also discourages their use.
- Solid stainless steel rebar has been used successfully in Europe and, to a limited extent, in the United States. When compared to mild steel rebar, this product has a high unit cost due to the higher price of the alloying metals used and the higher cost of fabrication.
- Graphite and glass filaments have an entirely different mode of reinforcement in concrete, requiring a high concentration of filaments dispersed throughout the concrete matrix. Uniform dispersion of fibers is a serious practical problem that has to be solved. The high cost of fibers, particularly graphite, is another discouraging factor.

For a replacement rebar to be used successfully in highways subjected to salt corrosion, it:

- must have complete reliability in terms of corrosion resistance,
- must be a one-on-one replacement for mild steel rebar in terms of structural properties, and
- must be easily produced in rebar shape by a low-cost process.

Aluminum bronze rebar is unique in that it can solve all of these problems. First, the corrosion resistance of aluminum bronze alloys has been demonstrated over many years and an extensive database¹ exists that justifies this position. The marine industry, where particularly harsh working environments exist, uses aluminum bronze alloys for ship propellers. In fact, the United States Navy specifies aluminum bronze for the large propellers used on its ships

There are three compelling reasons for using aluminum bronze rebar:

- It exhibits a high degree of corrosion resistance.
- It can be cut, welded and bent at the construction site without any fear that its corrosion resistance will in any way be affected or shortened. Corrosion-

resistance of rebar made from aluminum bronze will not degrade through rough handling.

- Aluminum bronze rebar can be engineered in the traditional fashion of mild steel rebar and can thereby be substituted one-on-one for mild steel.

The expected payoff of this innovative and unique corrosion-resistant rebar made from aluminum bronze alloy can be described as follows:

- complete confidence in the integrity of this rebar in long-term highway applications in corrosive environments,
- the lowest cost on a unit-weight basis of any of the existing solid, corrosion-resistant rebars, and
- the lowest cost on a life-cycle basis of any of the (epoxy) coated corrosion-resistant rebars.

The life of highways that are subjected to a significant corrosion environment and are reinforced with mild steel rebar is about five to seven years. The final expected payoff using aluminum bronze rebar is to extend the life of highways at least six-fold, to between 30 and 50 years, while maintaining the lowest possible material cost.

ALLOY BACKGROUND

ALUMINUM BRONZE

Introduction

Aluminum bronze is essentially a copper-base alloy with aluminum as the primary alloying element. Along with aluminum, these alloys may contain iron, nickel, manganese and silicon in varying percentages as alloying agents. The aluminum content of commercial aluminum bronze alloys varies from 4.0 % to 12.5%.

Equilibrium Diagram

Valuable information can be gained about alloys by studying the equilibrium diagram of that alloy system. The equilibrium diagram (sometimes called a phase diagram) reveals the metallographic phases that exist in equilibrium in the alloys over a range of temperatures and compositions. The equilibrium diagram of the copper-aluminum system is shown in Figure 1. This shows a range of aluminum content from 0% to 30%. The applicable part of the diagram is below 16% aluminum. This figure is also called a binary phase diagram because it shows equilibrium conditions of alloys having only two

constituents whereas commercial alloys as noted above have additional alloying elements. Since the research required to discover the equilibrium conditions of tertiary and quaternary alloys is inordinately difficult, the binary diagram is useful to refer to and pertinent information can be gained since the presence of other, smaller amounts of alloying alloys shifts the ordinate of the diagram.

From the equilibrium diagram in Figure 1, it can be determined that alloys to the left of the 9% composition line are single phase alloys; the phase being a solid solution of aluminum in copper. The alloys to the right of the 9% aluminum line are far more complicated, consisting of multi-phases. That part of the diagram contains a mechanism for hardening by heat treatment similar to what we see in the iron-carbon diagram. Since copper is the highest valued constituent in aluminum bronze, alloys containing less copper are more cost-efficient but metallurgical processing may be complicated by the fact they are heat-treatable.

Alloy Selected

The aluminum bronze alloy that was selected for testing is designated as Copper Alloy C95800². This alloy was preferred because of its high resistance to sea-water corrosion, high mechanical properties and low unit cost. It was felt that any technical issues arising from heat treatment could be dealt with. Table 1 shows the nominal chemical composition of C95800.

**TABLE 1 Nominal Composition
of Aluminum Bronze Alloy
C95800**

Element	% Composition
Copper	81.3
Nickel	4.5
Aluminum	9.0
Iron	4.0
Manganese	1.2

DUCTILE IRON

Ductile iron is a special type of cast iron. Cast iron is a very brittle material because most of the carbon (about 4%) exists as acicular graphite flakes that have an embrittling effect on the alloy. Ductile iron is a special case since the discovery that metallic magnesium and/or metallic cerium added to molten cast iron causes the alloy to solidify with the graphite having a spheroidal shape. Since this graphite shape is nonembrittling, the

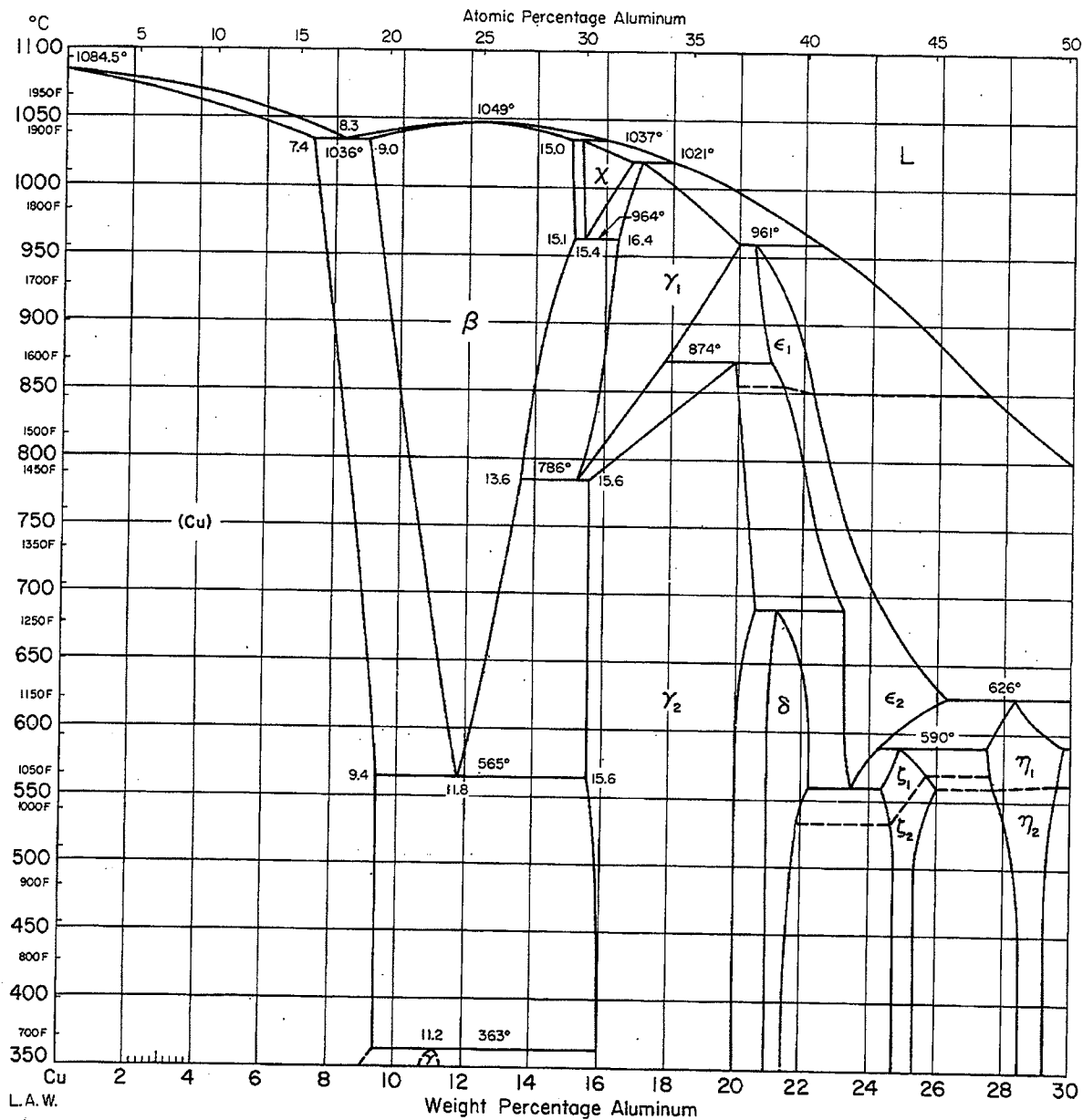


FIGURE 1 Equilibrium diagram of the copper-aluminum system.

alloy has high ductility and excellent mechanical properties.

Ductile iron is almost always produced in the form of foundry castings, although it can be hot rolled. Almost all of the production of mild steel, on the other hand, is not cast, but is hot rolled into bars, sheets and structural shapes. Ductile iron should hold some interest for the construction industry as a reinforcement for concrete for a number of reasons:

- lower cost feed material,

- lower cost production process, and
- environmentally benign process as compared to steel.

Lower Cost Charge

Since ductile iron has higher carbon and silicon than mild steel, the scrap material going into the furnace is less refined and therefore lower cost. For example, ductile iron can be made directly from pig iron without the refining process that is required of mild steel. The scrap

used for making ductile iron has a limited use for mini-mills because it can not be refined in the electric furnace.

Lower Cost Process

The production melting furnace used to produce ductile iron is called a cupola furnace. This melting furnace has been in use for decades and is significantly different from the electric arc furnace in many ways. It is unique in that the feed of scrap, coke and flux is charged into the top, and molten iron (and slag) pours from the bottom. Air is blown in near the bottom of the furnace to burn the coke and melt the iron. This is a truly continuous melting operation and, if operated with a continuous casting unit, would yield significant cost savings. Cupolas can be operated for months and even years, stopping only for maintenance and relining.

More Environmentally Benign

Ductile iron is produced from a cupola furnace fired by a fossil fuel. From an energy standpoint, cupola furnaces are three times more efficient than electric arc furnaces since cupolas use fossil fuels whereas electric arc furnaces used for mild-steel melting use electric power. Electricity is mostly produced from fossil fuels at efficiencies below 37%.

Replacing mild steel rebar with ductile iron rebar would have a positive impact on the environment by reducing waste products from the steel-refining process. Approximately 10% of the production of steel results in waste, consisting of bag house dust, slag and carbon dioxide, all of which cause pollution and/or require costly disposal.

STEEL

Almost six million tons of mild steel rebar are produced in this country annually. In the marketplace, mild steel rebar is considered a commodity item. Most mild steel rebar is produced by small, non-integrated steel plants from steel scrap that is melted in electric arc furnaces. Impurity elements such as copper, zinc and lead in the steel increase over time because of recycling of steel scrap, particularly that coming from automobile bodies. This is worrisome, but the mechanical properties of mild

steel are considered more than adequate to meet concrete reinforcement requirements. Rebar steel has a low carbon and a low alloy content.

CUSTOM-MADE REBAR

INTRODUCTION

Aluminum bronze bar is an attractive candidate for corrosion-resistant rebar because of its known corrosion resistance to chloride ion. In addition, aluminum bronze can be alloyed from low-cost recycled materials. A critical aspect of the corrosion testing of aluminum bronze bars is the nature and cost of the production method. There are many methods of producing aluminum bronze bars and, in fact, this product is available on the open market today. It makes no sense to test any of these products because the cost of both the production process and the alloy are high, and therefore eliminate their consideration as a competitive corrosion-resistant alloy to stainless steel for rebar. Stainless steel rebar resists corrosion successfully, but it costs approximately ten times more than mild steel rebar. An alloy rebar having equal corrosion resistance to stainless steel at a reduced cost would be both desirable and directly applicable to solving the rebar corrosion problem.

THE PROCESS

The unavailability of continuous cast aluminum bronze rebar for testing purposes made it necessary to produce a small quantity of samples by a non-continuous casting process. The assumption was that this was valid as long as the solidification rate and the integrity of cast structure reflect continuous casting characteristics. The sand molding process was selected as being the most suitable casting process. Structural integrity of the samples would be verified through use of radiography.

This casting process consists of making a mold from sand bonded with clay using a split matchplate pattern. Figures 2 and 3 show the top and bottom (cope and drag) details of this matchplate pattern required to custom-make rebar using this process.

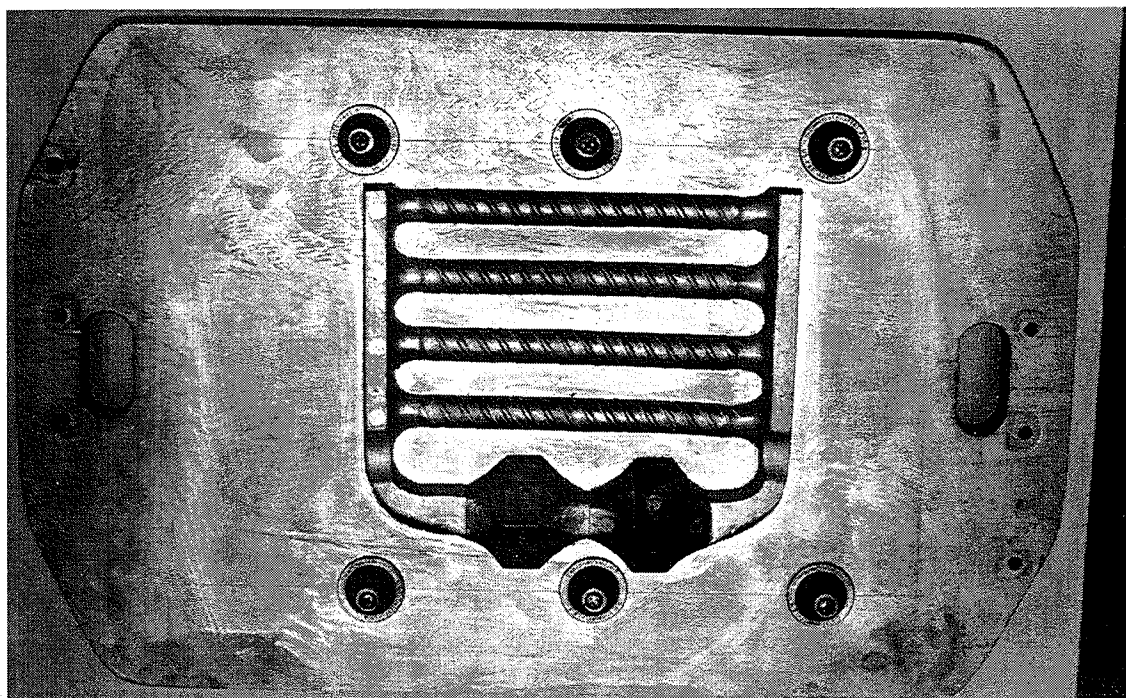


FIGURE 2 Foundry tooling with running system, drag side.

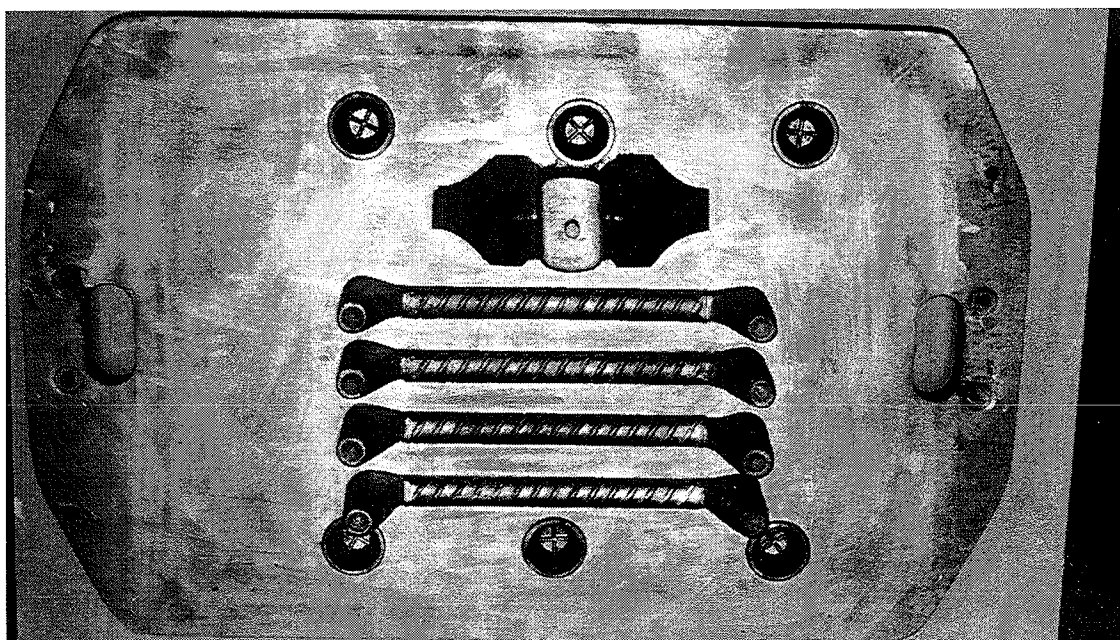


FIGURE 3 Foundry tooling with running system, cope side.

Four split patterns for #6 rebar, 7 inches long, are mounted on the matchplate foundry tooling. Also shown is the running system by which molten metal is poured into the mold. The running system consists of downsprue, filter, runner, gates and risers.

The design of the running system primarily determines the rate of solidification and integrity of cast structure and, therefore, the quality of the rebar castings. The running system is largely designed by empirical methods based on a great deal of experience. Very often, the production of specified quality is not accomplished with the first design. In the case of aluminum bronze rebar, it took three tries to arrive at the specified quality.

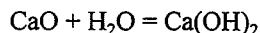
EVALUATION

Radiography was the nondestructive method used for qualifying the aluminum bronze rebar. Quality was established by comparing with ASTM E 192 Reference plates. Internal casting integrity was acceptable since radiographic quality was equal to or less than the severity of defects as delineated in the standards.

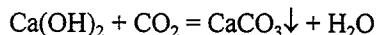
CORROSION TESTING

RATIONALE FOR CORROSION TESTING

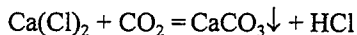
Most of the corrosion testing of rebar alloys is done at a controlled pH of 12, because the pore solution of concrete has been tested at this level of alkalinity. It is, however, obvious that reinforcing bar may be exposed to a varying pH during the lifetime exposure of concrete to the elements. The high pH of the pore solution—it is believed—comes primarily from the hydration of the free lime in the cement. The chemical reaction is:



A second chemical reaction, carbonation, follows the first because air contains carbon dioxide and precipitates the calcium as calcium carbonate as follows:



A third reaction is thought to occur when calcium chloride deicing salts are used:



This neutralizes the calcium hydroxide that may be present. It also decreases the pH of the pore solution.

Moisture enters concrete through two mechanisms: the porosity of the concrete or micro-cracks due to stresses. Moisture exits the concrete due to drying and hydraulic pumping caused by the dynamic loading from vehicles passing over these channels. These events result in:

- 1) leaching of the calcium from the interstices of the concrete, and
- 2) precipitation of the calcium from calcium hydroxide.

The events listed above causes the eventual reduction of the alkalinity of the pore solution towards 7. The figure below illustrates how the pH can change with time. A sample of crushed mortar³ was mixed with water in the ratio of 1:50. After 24 hours, the water was measured for pH, decanted and fresh water added. This was repeated for 25 days. Figure 4 shows the results.

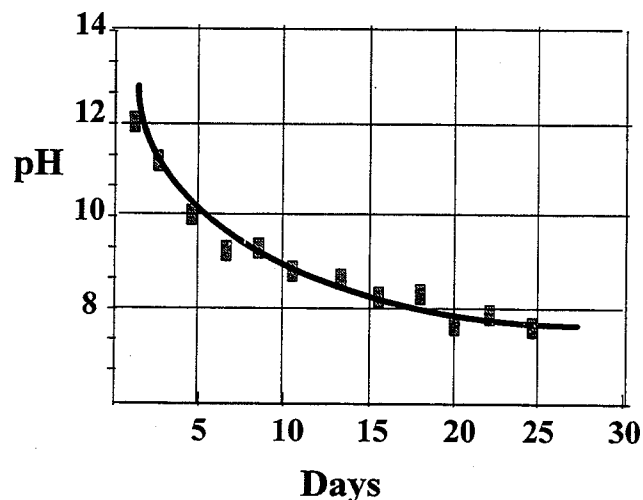


FIGURE 4 Reduction of pH of a suspension of crushed mortar in water when water is decanted daily.

These data suggest that corrosion rate determinations should be done over a range of pH, for example, from 12 to 7.

EXPERIMENTAL PROCEDURE

The work carried out in the course of this investigation involved the use of DC potentiodynamic polarization to evaluate the corrosion behavior of aluminum bronze, ductile iron and mild steel reinforcing materials in a 3.5% NaCl solution with the pH adjusted to 12 and 7 through the addition of 0.32M Ca(OH)_2 .

The electrochemical test specimens were prepared from transverse sections of rebars onto which insulated lengths of copper wire were spot-welded. The assemblies were mounted in fiber-glass resin, and then the exposed transverse surfaces were prepared for electrochemical corrosion testing by grinding to a 600 grit finish. The specimens were then degreased using alcohol in an ultrasonic cleaner, and the edges were masked off with epoxy resin in order to prevent crevice corrosion.

The corrosion flask was suspended in a water bath which was thermostatically controlled at $25 \pm 1^\circ\text{C}$ to ensure a constant temperature for the duration of the scan. Also, high purity argon was bubbled through the solution for one hour before testing was started, and was continued during the test. This was done to ensure that the solution was properly deaerated and to promote stirring, which would minimize concentration gradients at the metal surface by continually supplying fresh solution to the metal surface.

The corrosion tests were carried out in a round-bottomed flask which had been modified by the addition of extra necks to permit the introduction of a saturated calomel reference electrode, two graphite counter electrodes and the gas bubbler (Figure 5). This configuration was suspended in a water bath and connected to a Princeton Model 273 Potentiostat for the DC scans.

RESULTS AND DISCUSSION

The DC scans showed good reproducibility. The results obtained appear in Table 2 at a pH of 12 and in Table 3 at a pH of 7. Aluminum bronze is superior to both steel and ductile iron at both pH levels. Ductile iron is slightly better than steel at pH of 12 and considerably better than steel at a pH of 7 (Figure 6). The results indicate that aluminum bronze has a much lower corrosion rate at the free corrosion potential E_{corr} than either mild steel or ductile iron.

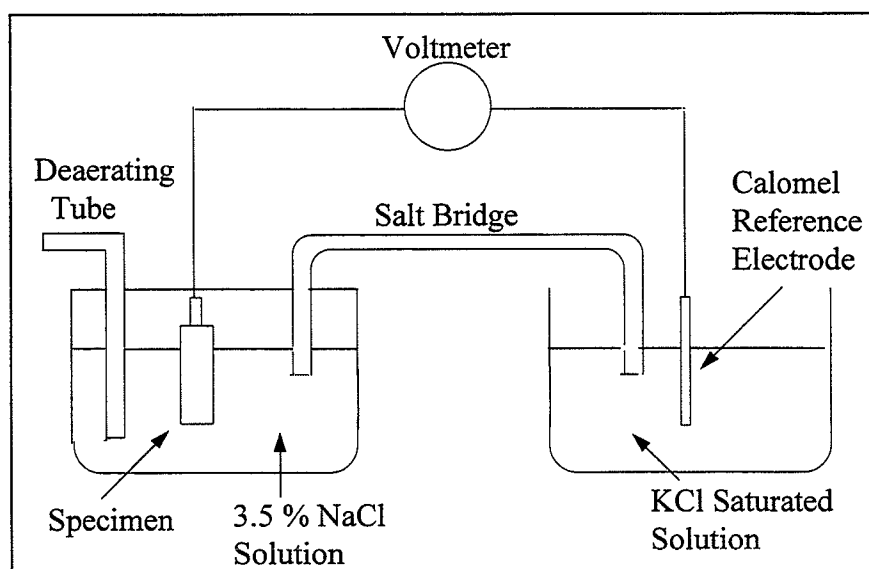


FIGURE 5 Schematic of set-up for determination of corrosion potential.

The specimens for the DC scans were conditioned at a potential of -700 mV below E_{corr} for ten minutes in the testing medium, before initiating the scan at this potential. This was done to destroy the passive layer and to remove any contamination on the metal surface which may have been picked up during the preparation process. Scanning was carried out anodically at a rate of 1 mV per second to a final potential of 1600 mV and the scans were performed in triplicate. The general corrosion rates were determined through the linear polarization technique.

TABLE 2 Polarization Results at pH 12

Alloy	Parameter	Test 1	Test 2	Test 3	Mean	Std. Dev.
Bronze	Corr. rate (MPY)	4.7	6.5	8.5	6.6	1.577
	E_{corr} , mV	-1009	-967	-1001	-992	18.200
Steel	Corr. rate (MPY)	68.5	87.4	152.4	102.8	35.915
	E_{corr} , mV	-1023	-1046	-1041	-1037	0.912
Ductile	Corr. rate (MPY)	74.4	96.9	114.6	95.3	16.432
	E_{corr} , mV	-1070	-1051	-1008	-1026	18.117

TABLE 3 Polarization Results at pH 7

Alloy	Parameter	Test 1	Test 2	Test 3	Mean	Std. Dev.
Bronze	Corr. rate (MPY)	1.9	2.7	1.8	2.1	0.403
	E_{corr} , mV	-470	-474	-460	-468	5.888
Steel	Corr. rate (MPY)	27.6	30.4	29.9	29.3	1.219
	E_{corr} , mV	-925	-945	-945	-938	9.428
Ductile	Corr. rate (MPY)	8.5	10.4	9.4	9.4	0.776
	E_{corr} , mV	-926	-932	-898	-919	14.817

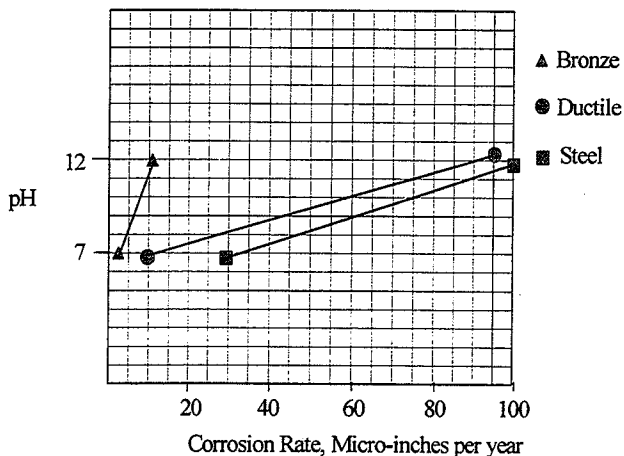


FIGURE 6 Corrosion rates of three alloys to chloride ion corrosion.

MECHANICAL PROPERTIES

METHOD

Mechanical property testing was performed to ASTM A370 specification on bars machined to R1 shape having a 0.505-inch diameter (Figure 7). Table 4 shows the values obtained on the three alloys: mild steel, ductile iron and aluminum bronze. Samples of aluminum bronze

and ductile iron rebar were selected from the lots of bars custom-made for this investigation. Samples of mild steel rebar were selected at random from a commercial source.⁴ The mechanical properties results of the mild steel rebar passed the requirement of the ASTM specification.⁵

DISCUSSION OF MECHANICAL PROPERTY RESULTS

Mild steel

The mild steel alloy used for most applications of reinforcing concrete is low in carbon and does not contain any deliberated added alloying elements. This is a tough, reasonably strong and ductile alloy. The strength of the mild steel rebar originates from the basic composition but is greatly influenced by the hot-rolling operation. Hot rolling takes place at approximately 1850°F. Since the steel cools fairly rapidly, the steel bar gets some strain hardening at a lower temperature. The result is an increase in yield strength. This low-carbon, low-alloy steel was the lowest-cost metallic material available at the time for use as concrete reinforcement; therefore, specifications that were written for rebar actually described the properties of mild steel rather than being written to meet a requirement. Higher mechanical properties of steel alloys can be obtained by increasing the carbon content, adding certain alloying elements and heat treating. However, not a great deal is gained in

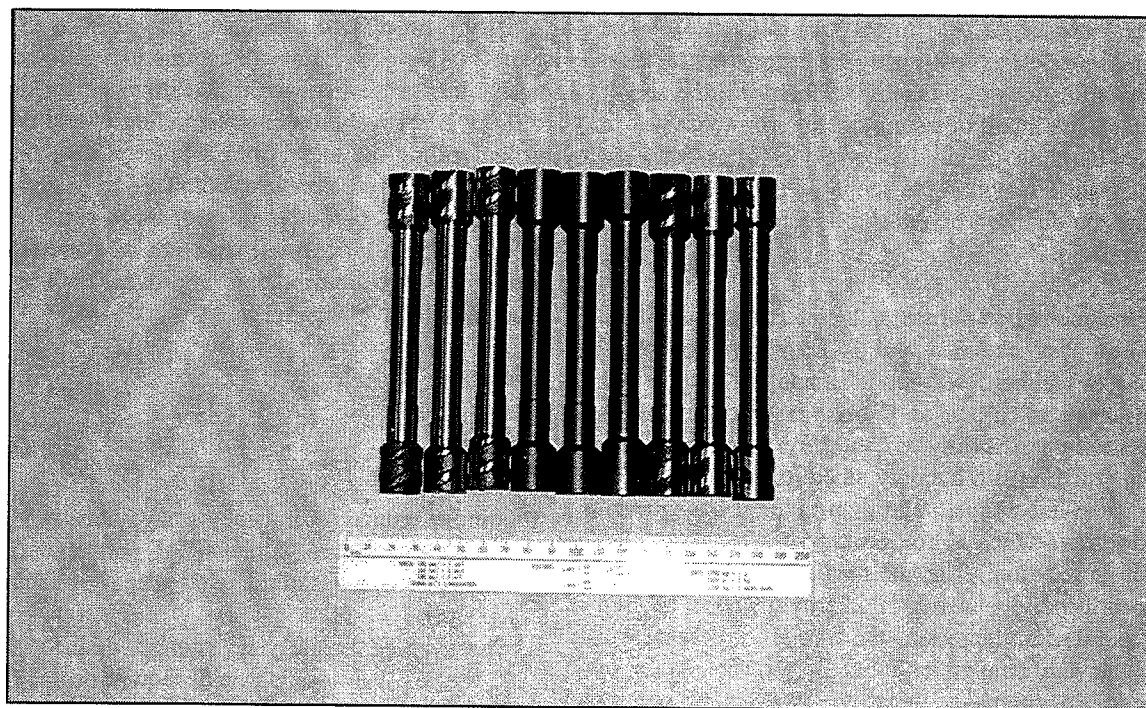


FIGURE 7 R1 test bars machined to 0.505-inch diameter.

TABLE 4 Mechanical Properties of Three Rebar Alloys

Sample No.	Yield Tensile ksi	Ultimate Tensile, ksi	Elongation, %
Bronze			
B1	40.4	85.4	9.0
B2	40.0	82.5	9.0
B3	40.1	83.2	9.0
Average	40.2	83.7	9.00
Ductile Iron			
D1	49.8	78.1	9.0
D2	49.7	76.8	7.0
D3	50.3	77.0	7.0
Average	49.9	77.3	7.7
Mild Steel			
S1	76.5	119.0	19.0
S2	77.5	118.9	18.0
S3	77.1	118.5	18.0
Average	77.0	118.8	18.3

most applications by using stronger steel rebar. Materials and processing technologies continuously change, such that it becomes necessary to re-examine the position of low-carbon, low-alloy steel as the most suitable alloy for reinforcing bar for concrete. For this reason, ductile iron was added to the list of alloys in this investigation. It

might be interesting to consider ductile iron as a competitor to mild steel for rebar applications.

Ductile Iron

The mechanical properties of the custom-made ductile iron rebar are also shown in Table 4. Here, the

mechanical properties are lower than mild steel. The mechanical properties can easily be improved to meet ASTM specifications by adjusting the composition and/or hot rolling. The intent of testing ductile iron rebar was to establish a baseline, mainly for corrosion properties. We did not consider it within the scope of this investigation to process the ductile iron rebar to meet mild steel rebar specifications.

For documentation purposes, the microstructure of the ductile iron was obtained and is shown in Figure 8. Three phases can be observed. The smallest and darkest rounded shape is carbon as a graphite spheroid. This shape contributes ductility to the alloy as compared to cast iron which has no ductility since its graphite has an acicular flake-like shape. The light-colored background is called ferrite, which is iron containing a small amount of carbon in solution. The intermediate colored shape is called pearlite and consists of alternate layers of iron carbide and ferrite. Increasing the amount of pearlite will increase the yield strength of ductile iron. The amount of pearlite can be managed through composition control or/and heat treatment.

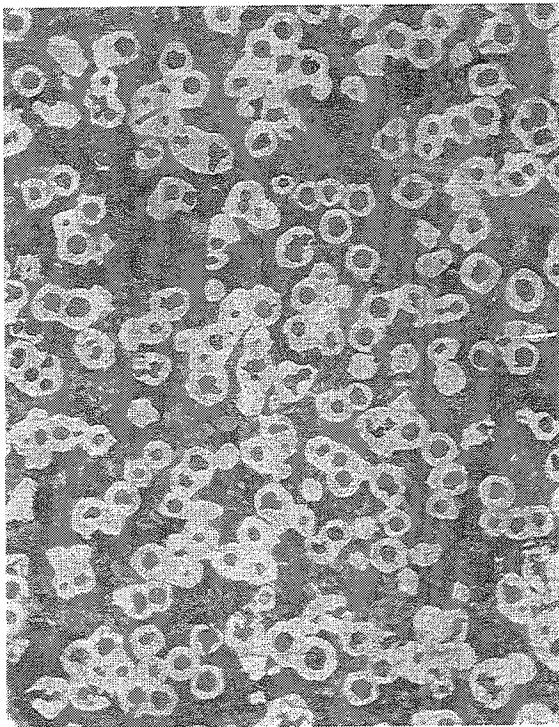


FIGURE 8 Microstructure of ductile iron at 100 magnification.

In the process of producing ductile iron in a rebar shape (which is not a commercial process), the mechanical properties would be further enhanced by hot rolling. Effectively, the microstructure would be refined by hot rolling the alloy from a billet size to rebar size. The homogenized structure would be expected to have higher ductility and strength properties since it is well known that working a cast structure of a metal or alloy through plastic deformation improves both the yield strength and the elongation.

Aluminum Bronze

Introduction

Aluminum bronze rebar samples have been produced by a custom process as a matter of convenience. The mechanical properties of the rebar appear in Table 4.

The average tensile yield strength 40.2 ksi does not meet the 65 ksi tensile yield requirement of ASTM specifications. This is not unexpected since the rebars have a cast structure with no further processing to increase strength properties. The first objective of this investigation is to show that aluminum bronze alloy has adequate corrosion resistance and then that the strength of the alloy can be increased by cold working the alloy to meet ASTM Specification requirements.

Increasing mechanical properties by cold working is a common metallurgical processing procedure called strain hardening. To illustrate this, Figure 9 shows the increase in yield strength of a brass alloy when it is subjected to varying reductions in area by cold rolling.

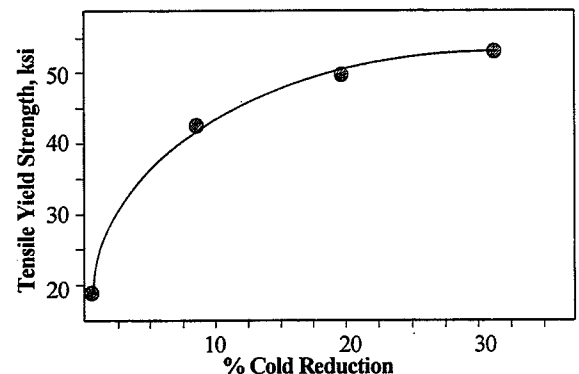


FIGURE 9 Tensile yield strength as a function of percentage cold reduction, brass alloy.⁶

Experimental Procedure

This part of the investigation deals with determining the tensile yield strength of aluminum bronze as a function of the amount of cold work applied.

Nine aluminum bronze rebars were machined to remove the rebar pattern on the surface. These bars were drawn down to the same diameter by a mechanical forming operation called wire drawing. Since the machined bars had random diameters, the percentage of reduction varied. The drawing operation was carried out at room temperature. The results are shown in Table 5.

TABLE 5 Reductions in Area of Aluminum Bronze Bars

Bar Designation	Original Diameter	Final Diameter	% Red. in Area
8	0.615	0.53	25.7
18	0.587	0.53	18.5
17	0.572	0.53	14.1
4	0.557	0.53	9.5
3	0.557	0.53	9.5
1	0.545	0.53	5.4
14	0.541	0.53	4.0
16	0.537	0.53	2.6
15	0.535	0.53	1.9

Figure 10 shows these bars after drawing. The top bar has not been drawn and shows the original length of the aluminum bronze bars. The bars are of varying length because they have been subjected to different reductions of area.

Tensile test coupons were excised from each of the cold worked bars and tested for mechanical properties. These results are shown in Table 6.

TABLE 6 Mechanical Properties After Cold Reduction

Bar	% Cold Reduction	Tensile Yield Ksi	Ultimate Tensile Ksi
8	25.7	77.9	8
18	18.5	76.5	10
17	14.1	76.8	8
4	9.5	60.8	8
3	9.5	68	8
1	5.4	61.2	5
14	4	50.2	5
16	2.6	47.7	5
15	1.9	41	4

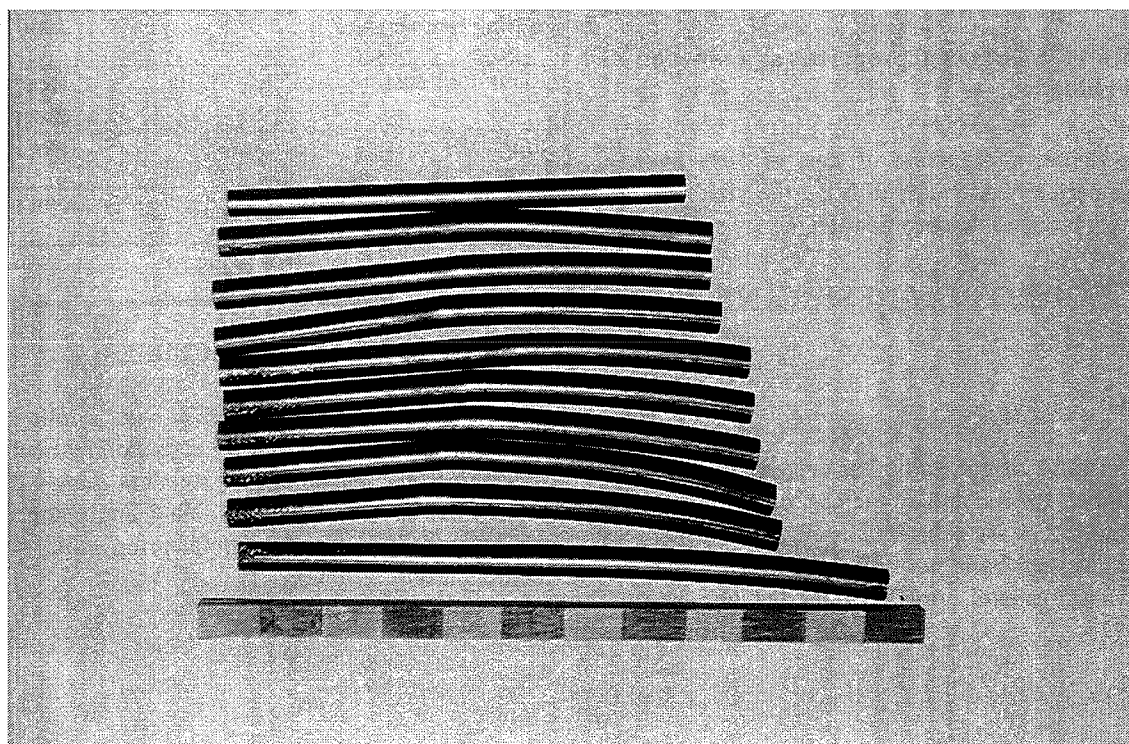


FIGURE 10 Photograph of aluminum bronze bars given various reductions in area.

Results and Discussion

We are particularly interested in the yield strength and the amount of cold work to which the bars must be subjected in order to meet the minimum yield strength as required by the ASTM specification for steel rebars. A plot of tensile yield strength as a function of reduction of area is shown in Figure 10. This shows clearly that the tensile yield strength of aluminum bronze can be increased by strain hardening. In this case, the strain hardening was cold working the aluminum bronze rods by drawing the rods through steel dies at room temperature.

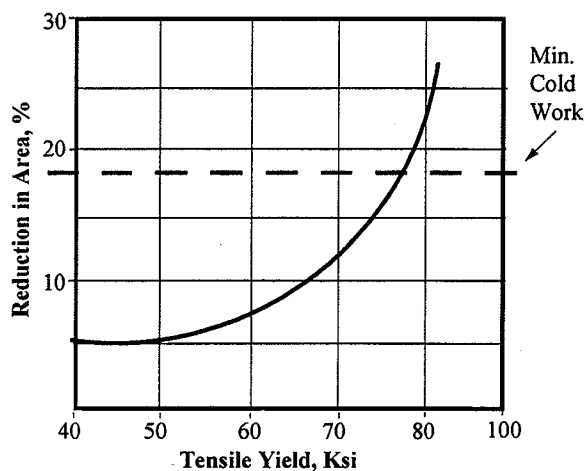


FIGURE 11 Mechanical properties as a function of cold reduction.

From the figure, a reduction of area of 18% by cold drawing is perfectly adequate to bring the yield strength of aluminum bronze into specification, i.e. over 65 Ksi.

COST: CORROSION-RESISTANT REBAR

INTRODUCTION

The market value of a metallic bar depends on the value of the materials therein and on the cost of manufacturing. Stainless steel bars are substantially higher in price than standard mild steel bars, not only because of the higher metallic values (nickel, molybdenum) but also because

stainless alloy is more difficult to process. When comparing the cost of bars made from aluminum bronze with that of mild steel, the material cost of aluminum bronze is higher (copper, aluminum) than mild steel, but the production costs are lower. This is explained by the lower melting temperature of aluminum bronze as well as by a simplification of processing since the aluminum bronze can be cast almost to net shape. On this basis, aluminum bronze alloy would qualify on a cost basis as the preferred corrosion-resistant alloy over stainless steel for reinforcing concrete.

ESTIMATED COST OF ALUMINUM BRONZE REBAR

The processing cost of aluminum bronze rebar is lower than mild steel because aluminum bronze:

- has a lower melting and pouring temperature, and
- does not require hot rolling.

The details are summarized in Table 7.

TABLE 7 Summary of Manufacturing Operations for Two Alloys

Operation	Mild steel Rebar	Aluminum Bronze Rebar
Pouring temperature	3000° F	2000° F
Continuous casting	5"X5" Billet	Near net shape
Rough hot rolling	Required	Not required
Finish hot rolling	Required	Not required
Finish draw	Not required	Required

COST OF BARS AND STRUCTURES

A recent paper⁷ discusses the cost implications of stainless steel as rebar used for corrosion resistance. The figure of \$1.20 per pound for stainless rebar—from that paper—has been inserted in Table 8 and compared with the estimated costs of manufacturing mild steel and aluminum bronze rebar.

TABLE 8 Cost Comparisons for Four Rebar Alloys

Cost per Pound	Mild Steel Rebar ⁸	Bronze Rebar ⁹	Stainless Rebar
Material Cost	\$0.05	\$0.70	
Continuous Casting	\$0.07	\$0.05	
Rough Hot Rolling	\$0.05	\$0.00	
Finish Hot Rolling	\$0.02	\$0.00	
Finish Draw	\$0.00	\$0.02	
Total Cost	\$0.19	\$0.77	\$1.20

CONCLUSIONS

Aluminum bronze alloy, C95800, showed high resistance to sea water corrosion as compared to mild steel and ductile iron. Ductile iron tested better than mild steel.

Custom lots of aluminum bronze rebar were produced by a low-cost process. The process entails the direct continuous casting of aluminum bronze to a near net size and shape of rebar followed by cold drawing the bar to finished size and shape. The hot rolling operation was eliminated entirely. The cold drawing operation at the

level of 18% cold reduction through drawing increased the strength of the aluminum bronze rebars to that of mild steel rebar, thus meeting ASTM Specifications.

Cost analysis of aluminum bronze rebar showed a cost of \$0.77 a pound as compared to \$1.20 a pound for stainless steel at today's metal prices.

RECOMMENDATIONS FOR FUTURE WORK

Stainless steel and aluminum bronze rebars exhibited exemplary resistance to corrosion when exposed to environments simulating deicing salts and marine atmosphere that are destructive to mild steel to chloride ion¹⁰. Since the cost of aluminum bronze rebars is approximately 35% less than stainless steel rebars, it is recommended that a next higher development phase be initiated for aluminum bronze rebars. This would cover the manufacturing of a small lot (1000 pounds) of aluminum bronze rebar by a scaled-down prototype process. This prototype process would encompass the continuous casting of the molten aluminum bronze and the cold drawing the bar into final rebar shape and size. This lot would be tested for mechanical properties and corrosion resistance and analyzed for production costs of the rebars since it would represent fully the product of a production manufacturing process. Large test panels and highway test sections would be poured.

¹Aluminum Bronze Alloys Technical Data, The Aluminum Bronze Advisory Service, Copper Development Association, London, England

²ASTM Specification B 505, *Standard Specification for Copper-Base Continuous Castings*

³Provided by Lone Star Industries, Maryneal, Texas

⁴Atra Corporation, Arlington, Texas

⁵ASTM Specification A 615/A 615M - 94, *Standard Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement*

⁶Metals Handbook, Vol. 1, 8th, Edition

⁷McDonald, D. B.; Sherman, M. R.; Pfeifer, D. W.; and Virmani, V. P., "Stainless Steel Reinforcing as Corrosion Protection". *Concrete International*, May, 1995, pp 65-70

⁸Private communication, F. Kenneth Iverson, CEO, Nucor Corporation

⁹Stein, D., The Scimitar Process, *National Institute of Standards and Technology*, 1995

¹⁰McDonald, D. B., Pfeifer, D. W., Blake, G. T., "The Corrosion Performance of Inorganic, Ceramic- and Metallic-Clad Reinforcing Bars and Solid Metallic Reinforcing Bars in Accelerated Screening Tests," Interim Report, Federal Highway Administration, Nov., 1995

