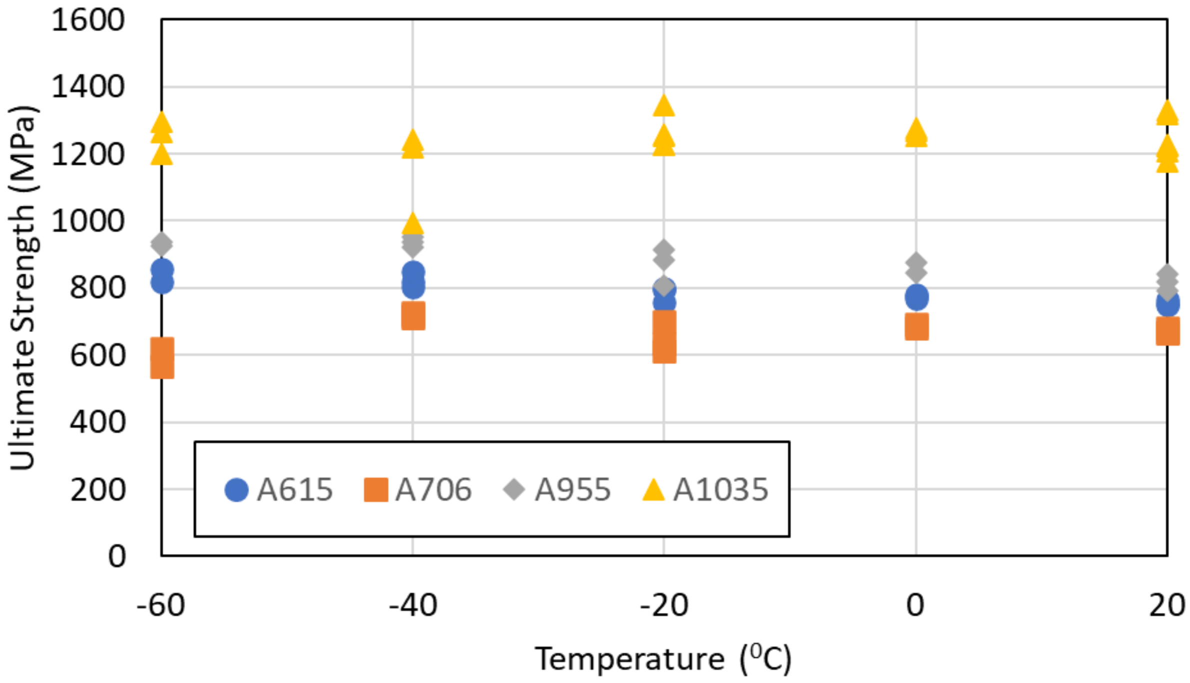

Fig. 10 Ultimate strength of steel alloys vs. temperature

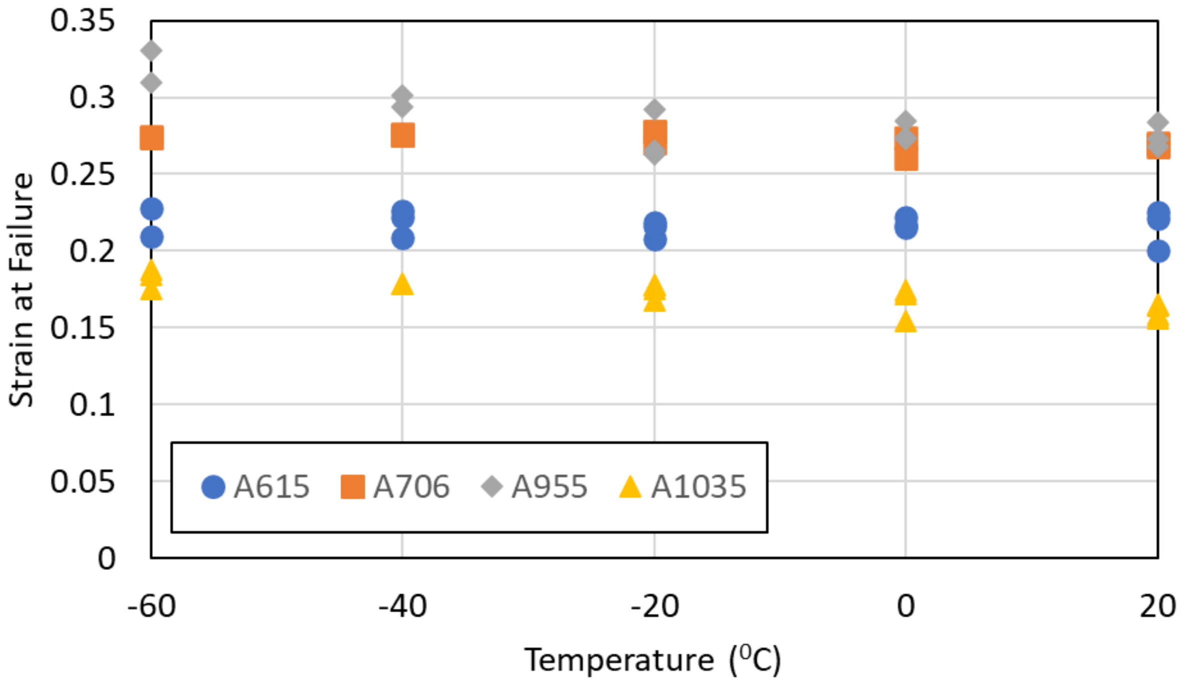

Fig. 11. Failure strain of steel alloys vs. temperature

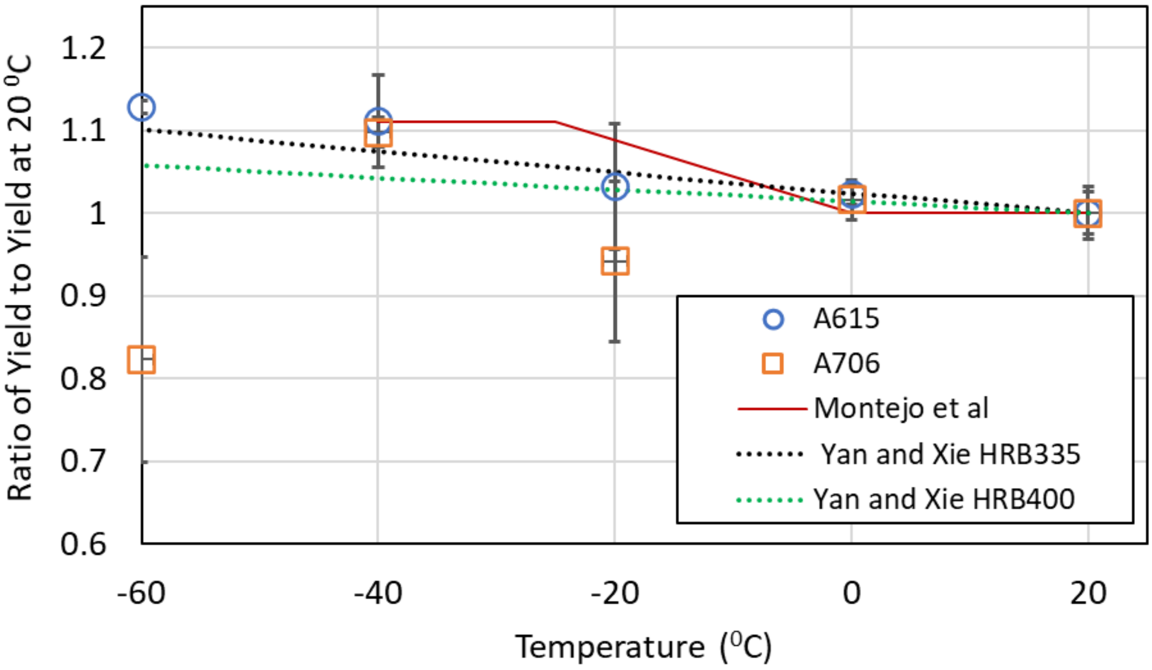

Fig. 12. Yield strength ratio to +20 °C

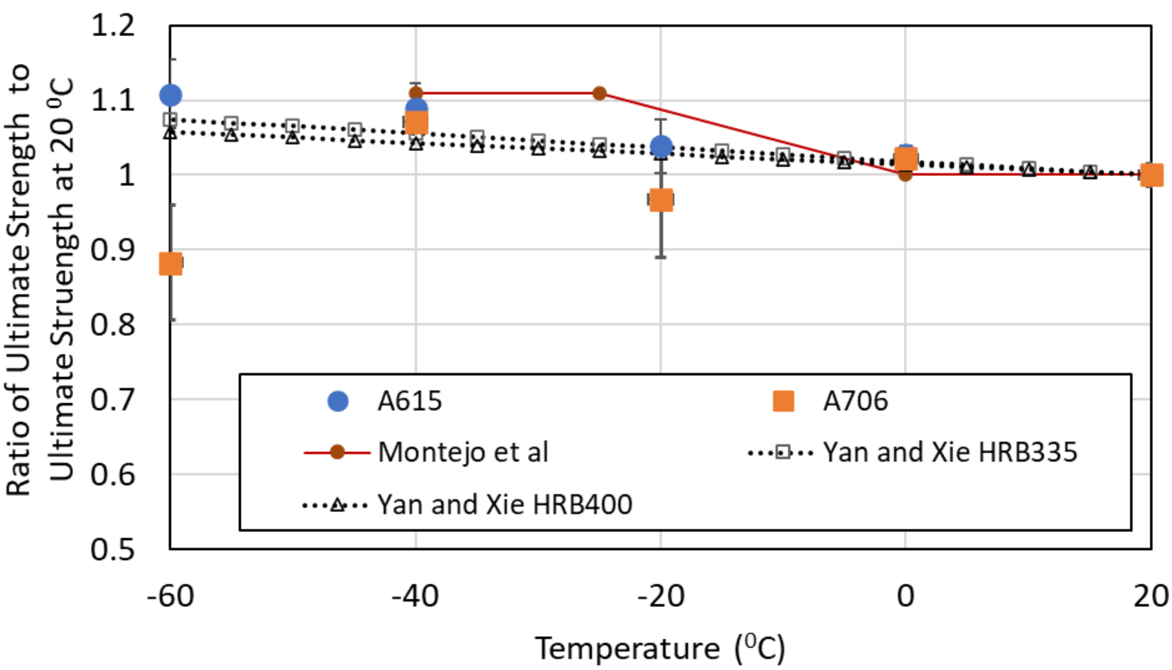

Fig. 13. Ultimate strength ratio to +20 °C

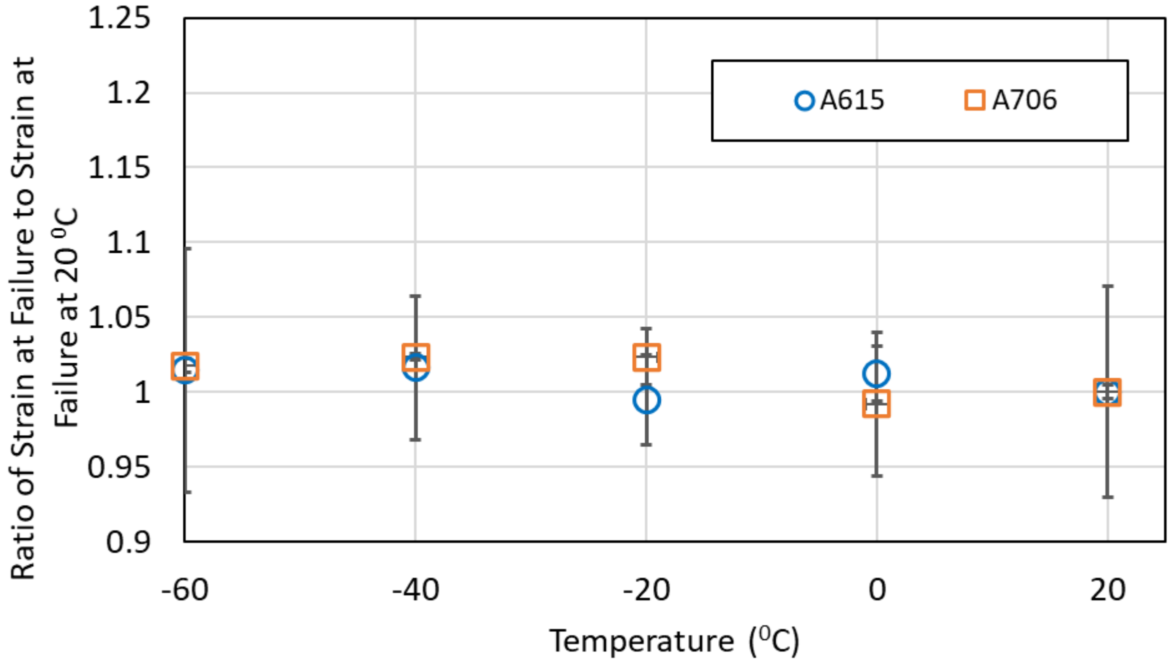

Fig. 14. Strain at failure ratio to +20 °C

The average values of the yield strength ratios make it clear that the yield strength of A615 increases as temperature decreases from +20 down to -60 °C, culminating in a 12.8% increase at -60 °C. No such trend is apparent for A706, as the average values are less than the 20 °C values for some temperatures, and greater for others. The average of the yield strength ratios for A615 are either within or very close to the range of ratios of the published relationships. Only the -60 °C is outside these bounds, and this is very close. It is difficult to see a trend in the A706 data. The average ratio for -40 °C is near the upper boundary of the region defined by the published ratios, whereas -20 and -60 °C are noticeably below. Except for the -60 °C data, the 95% confidence range falls within the region defined by the published ratios.

The overall trends for the ultimate strength of A615 and A706 are the same as those for yield strength. The ultimate strength for A615 is 10.8% greater at -60 °C than at +20 °C. The average of the ultimate strength ratios for A615 falls within the region defined by the published values except for -60 °C. However, if the flat line between -25 and -40 °C defined by Montejo et al were extended to -60 °C, the region defined by the published values would contain the A615 data for -60 °C. As with the yield strength ratios, the average ratios for A706 at -20 and -60 °C fall below the region defined by the published values. The 95% confidence range for -20 °C data falls within the published range, whereas the 95% confidence range for -60 °C does not.

The strain at fracture remains fairly constant with changing temperatures between +20 and -60 °C. While explicit equations for the strain at failure have not been published by other researchers, the effect of temperature on ductility for carbon steels at quasi-static is typically either a slight decrease with temperature or no effect.

The A955 and A1035 alloys display increasing ultimate strain at failure as temperature decreases from 20 °C to -60 °C. The other two alloys did not exhibit a discernable change in strain to failure. Previous research suggested either a slight decrease or no change in ductility as temperatures decrease. However, these studies were focused on carbon or low alloy steels that are more similar to A615 or A706 than A955 and A1035 alloys.

The ratios of yield strength for both A955 and A1035 tend to be outside the range of the published relationships. Average values for temperatures from 0 to -60 °C are above the range of published relationships for A955, with the yield strength being 15.4% greater at 60 °C compared to +20 °C. The 95% confidence for A955 at -40 °C is entirely outside the range of published relations, and the 95% confidence for -60 °C would just barely be in the range if the Montejo, et al. relation were extended to -60 °C. Average values for A1035 are below the range of published relations for -20, -40 and -60 °C. The 95% confidence range for -40 °C is completely out of the published range. These data suggest there is effectively no change in yield strength for temperatures ranging from +20 to -60 °C for A1035.

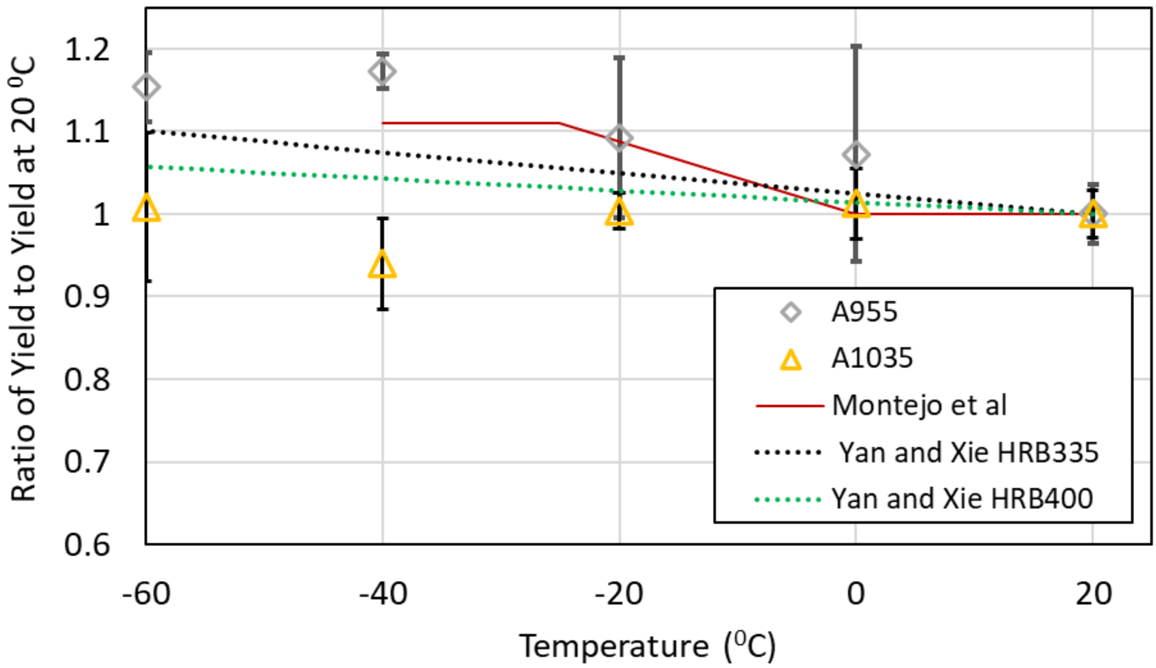

Fig. 15. Yield strength ratio to +20 °C

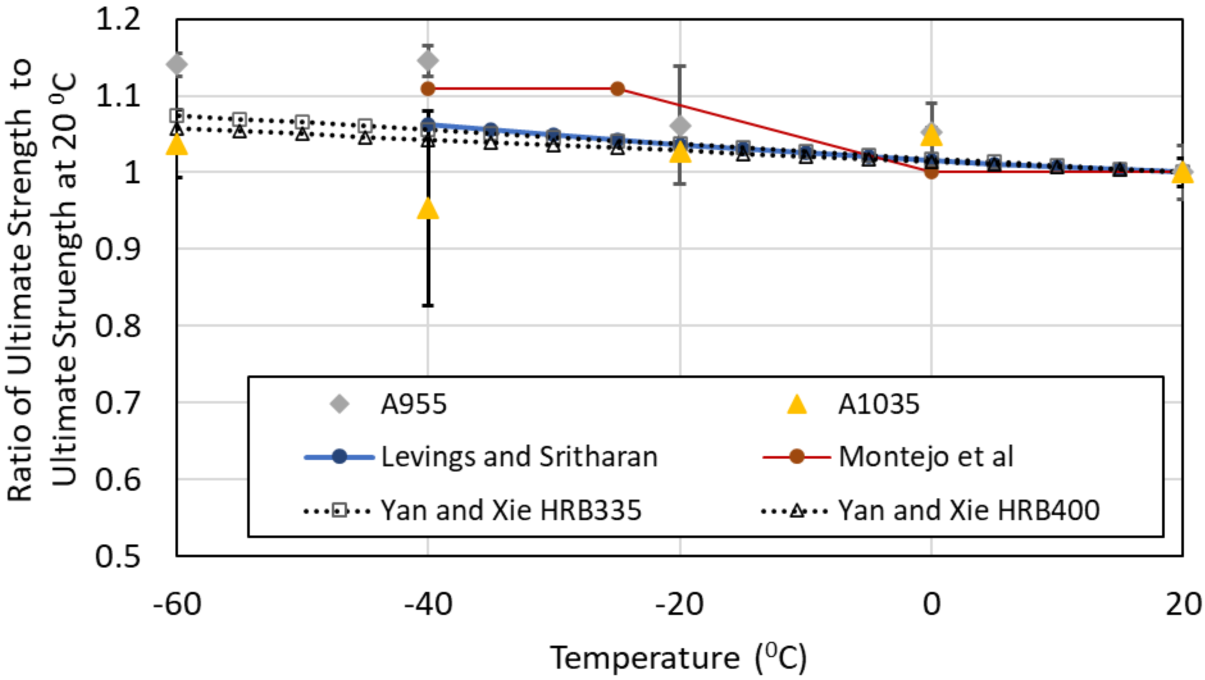

Fig. 16. Ultimate strength ratio to +20 °C

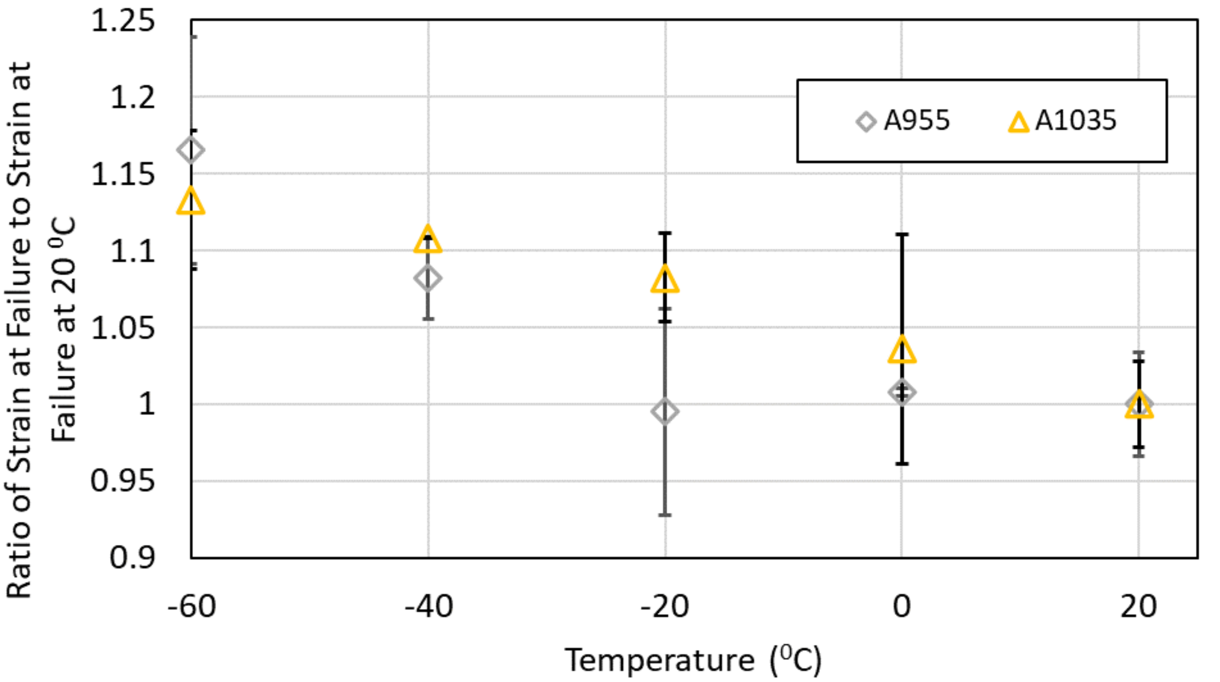

Fig. 17. Strain at failure ratio to +20 °C

Similar trends are exhibited by A955 and A1035 for ultimate strength ratios as yield strength ratios. The A955 average ultimate strength ratios are greater than the published relationships for -40 and -60 °C. The ultimate strength of A955 is 14% greater at -60 °C than at +20 °C. The 95% confidence intervals at both -40 and -60 °C are slightly outside the range of published relations. As with the yield strength, there is effectively no change in the ultimate strength of A1035 for temperatures ranging from +20 to -60 °C.

Both A955 and A1035 exhibited an increase in strain at failure as temperatures decreased from +20 to -60. Strain at failure for A955 was relatively constant from +20 to -20 °C, and then increased steadily as temperature decreased to -60 °C. The strain at failure for A955 was 16.5% greater at -60 °C compared to strain at failure for +20 °C. The strain at failure for A1035 exhibited a steady increase as temperature decreased from +20 to -60 °C. The strain at failure for A1035 was 13.2% greater at -60 °C compared to strain at failure for +20 °C. Previous research on reinforcement steels suggested either a slight decrease or no change in ductility as temperatures decrease. However, these studies were focused on carbon or low alloy steels that did not have the chromium content that A955 and A1035 alloys have.

3. CONCLUSIONS

The effects of temperatures ranging from +20 to -60 °C on the yield strength, ultimate strength and strain at fracture of four types of steels used as concrete reinforcement were evaluated. Two of the steels considered, carbon steel A615 and low alloy steel A706, are commonly used in the U.S. Two of the materials, stainless steel A955 and low alloy chromium steel A1035 have a significant chromium content. While less commonly used than A615 and A706, their corrosion resistance can be useful under certain design conditions.

Previous research on the effect of cold temperatures on the mechanical properties of rebar have focused on A615 and A706, or similar carbon-based steels. Relationships for the effect of temperature on yield strength proposed increases in both yield strength and ultimate strength ranging between 5 to 11% greater at -40 or -60 °C compared to those values at 20 °C, with either no change or a decrease in ductility as temperature decreases from +20 to -60°C. The trends observed in this study for A615 and A706 verified these previously published relationships for these steels.

However, results for the two corrosion resistant steels, A955 and A1035 were slightly outside the ranges of the previously published relationships. Cold temperatures have a slightly greater effect on both yield and ultimate strengths for A955 than the previously published relationships, with increases at -60 °C of 15.4% and 14.0% for yield and ultimate strength, respectively, compared to those values at +20 °C. Temperatures ranging from +20 to -60°C° had effectively no effect on yield and ultimate strengths of A1035. The strain to failure for both of these materials increased as temperatures decreased from +20 to -60 °C.

The implications of temperature effects on reinforcement steel behavior for the design of reinforced concrete structures in cold regions are complex, and will require additional study. Both the strength and stiffness of concrete will be affected by temperature as well. These changes can interact to affect the failure mechanism for a structural component, cause additional loads to be transferred through stiffer components, and change the load capacity of connections in the structure. In light of these potential effects, it is not clear that it is possible to make a conservative assumption regarding material properties. Instead, a bounding approach should be considered. The results presented in this paper will assist in these analyses.

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