Development Length In Recycled Steel Bar Reinforcement

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Abstract

Reinforcing concrete with steel introduces a component of ductility that is impossible to attain in concrete alone due to its inherently fragile nature. This presupposes that there is such bonding between the two materials that at the moment of failure of the concrete, steel holds onto the concrete and simultaneously yields to facilitate an overall ductile deformation. The tendency for steel bars to possess excessive strength makes it impossible for timely permanent deformation to occur, leading to failure in concrete long before the steel reinforcement yields. Steel bars normally have a yield stress range around which the concrete-steel composite is designed. Due to the unpredictable nature of recycled steel composition however, the resulting steel bar strength values are hard to guarantee even in the same production batch. In this paper, the tendency for steel bars to have higher than predicted yield stress levels is studied using a statistical-probabilistic approach. The batch of 72 recycled steel bars in this study subjected to monotonic loading to failure and spark spectroscopy shows a normal distribution of steel yield stresses. The cumulative distribution function $P(X \geq \chi)$ was subsequently evaluated for 550Mpa. Over 20% of the samples were found to be above the 550Mpa design value and therefore the development length, which is directly proportional to the steel bar yield ends up with the same probability stretch. Direct proportionality between the growing yield values and Boron content has also been graphically demonstrated.

Keywords: Reinforcement Bars, Recycled Steel, Concrete, Development Length, Yield Stress.

1. INTRODUCTION

In reinforced concrete construction, the efficiency with which forces are transmitted between the steel reinforcement and concrete is the most important feature in the effectiveness of the resulting composite and is determined by the bond between the reinforcing bars and the concrete [1]. This in turn depends on the chemical adhesion between the bar and the concrete, the frictional forces arising from the roughness of the steel-concrete interface and the mechanical anchorage offered by the bar ribs against the concrete surface [2].

Chemical adhesion mainly plays its part at relatively low stress levels. FIB , 2000 [3] actually suggests that this occurs in uncracked concrete at shear stress values $\tau \leq (0.3\text{-}0.8)\tau_c$ while How-Ji *et al* 2000 put it at 0.25 mm relative slip; τ_c being the allowable concrete shear stress. Once adhesion is lost at higher stresses, the bond is primarily provided by friction and the anchorage on the ribs of the bar. At much higher bar stress, however, the bond strength is fostered entirely by concrete anchorage on the bar ribs [4].

In a typical beam under flexural loading (Fig.1), flexural deformation of the beam creates tensional stresses which in turn result in bond stresses between concrete and the reinforcement. The bond stresses oppose the propensity of the steel bar to being pulled out of the concrete. They exist whenever the force in the reinforcing bar changes from one location to another along the bar.

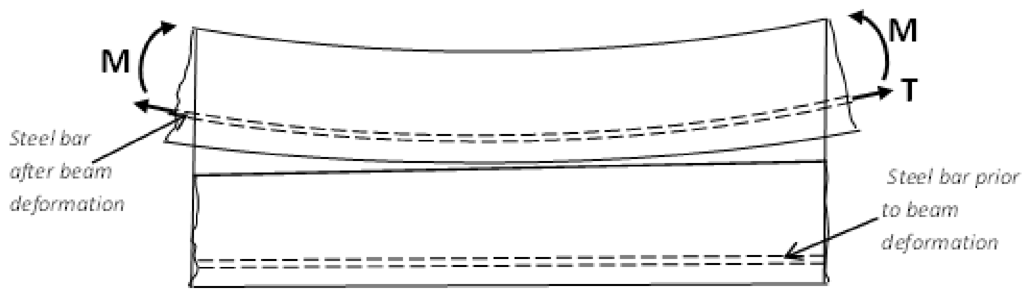

Fig.1: Action of moments and forces on reinforcement on bending beam

The bond stresses are finally translated into compressive stresses *c* acting perpendicular to the bar rib flanks and bearing forces *f* along them. The bearing forces are thus inclined to the longitudinal axis of the bar at an angle *α* (Fig. 2).

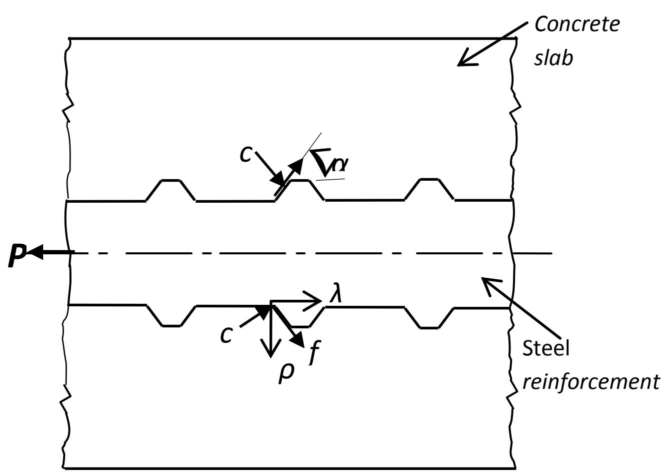

FIGURE 2: Bearing forces on bar ribs.

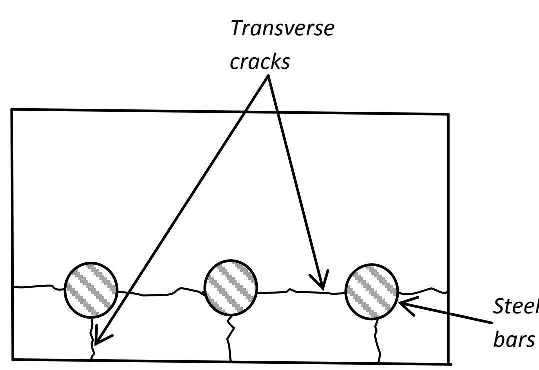

FIGURE 3: Splitting failure in reinforced concrete.

These may be resolved into radial (hoop stresses) and longitudinal components *ρ* and *λ* respectively (Fig.2). The radial stresses cause circumferential stresses around the bar which generate splitting failure (Fig.3). The load at which splitting failure develops is a function of the minimum distance from the bar to the surface of the concrete or to the next bar, the tensile strength of the concrete and the average bond stress [5]. In general, the smaller the distance from the concrete surface, the smaller is the required splitting load.

If these conditions are not met, splitting does not occur and instead, pullout failure ensues. In that case the bar and the ring of concrete between successive bar ribs pullout along a cylindrical failure surface joining the tips of the ribs so that the concrete shears parallel to the bar axis; the resultant crack propagating to the surface of the concrete element (Fig 4).

As slip progresses, the stress in the reinforcement reduces to zero and the beam subsequently behaves like plain concrete, giving in to immediate failure in a typical fragile mode. Since the purpose of reinforcing concrete is to impart ductility values otherwise unavailable in concrete alone, it is at this stage that the pullout can be prevented by designing the steel bar as the weaker element in the concrete-steel chain for if anchorage to the concrete is sufficient, the stress in the reinforcement should become high enough to lead the steel bar to its yield value.

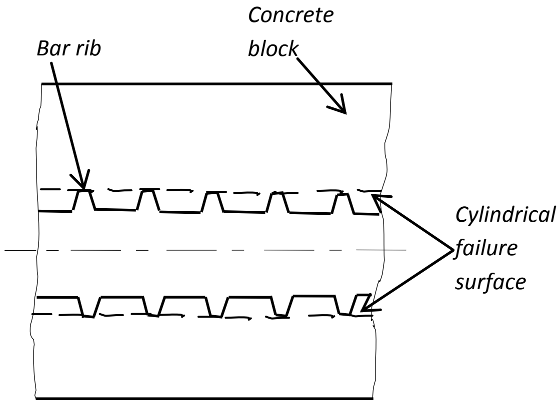

FIGURE 4: Pull out failure in reinforced concrete.

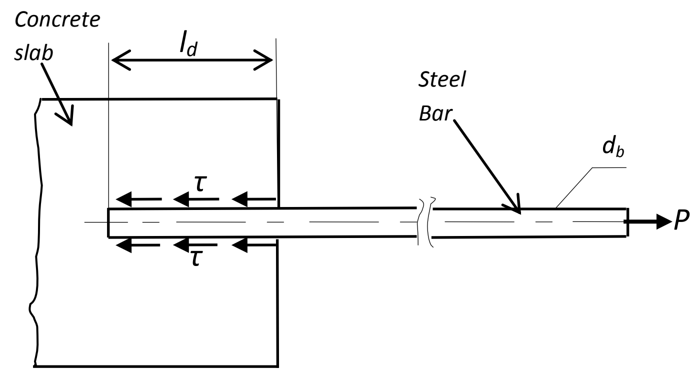

FIGURE 5: Development length and action of shear stresses.

The development length, l_d is the length of the reinforcement bar anchorage that will cause bond stresses equal to the yield stress of the reinforcement bar [6]. In order to make the steel bar the weaker part of the linkage (Fig.5), the shear stress in the concrete needed for pull out should be greater than the steel bar yield stress, that is; σ ≤τ;

$$\tau = P/\pi d_b\, l_d \leq \tau_c \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots i)$$

$$\sigma = \frac{4P}{\pi d_b^2} \leq \sigma_y \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots ii)$$

Combining *i)* and *ii)*

$$\pi d_b l_d \tau_c \geq \sigma_y \pi d_b^2/4$$

and

$$l_d \geq \left(\frac{\sigma_y}{\tau_c}\right)\frac{d_b}{4} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots iii)$$

where:

- l_d is the development length.
- σ_Y the yield stress of the steel reinforce bar.
- τ_c the allowable concrete shear stress at the concrete/steel interface.
- d_b the diameter of the steel bar.

Equation *iii)* shows that the value of σ_y/τ_c determines l_c for a given bar diameter and that the value of l_c increases lineally with σ_y.

There are several concrete types in use in the civil engineering practice and most common of all are normal concrete, high strength concrete and high performance concrete [7]. To each of these types, there is a corresponding value of the allowable stress, τ_C. For the purpose of this study, concrete refers to normal concrete variety (normal weight or normal strength concrete) with a yield point of up to 40Mpa.

The high strength thermo-mechanically treated (TMT) bars are of minimum of 460 Mpa upper yield [8]. Higher yields are limited to 550 Mpa for longitudinal reinforcement [6] and projections are normally based on this strength maximum level. To make the bar the weaker part of the steel-concrete composite link, the yield strength of the bar must be within certain limits for a given type of concrete so as to facilitate a pre-calculation of the development length.

The yield strength of steel is dependent on its composition and for recycled steel this is a function of its overall residual element content. Tian *et al*, 2010 [9] suggest that basically all residual elements in recycled steel contribute to an increase in strength with an associated ductility loss and that these individual hardening effects are additive and increase with particular alloying element content. Additionally Porowski *et al,* 2007 [10] in their publication 'Micro Addition of Boron and Vanadium in Austempering of Ductile Iron' submit that certain micro-elements such as Boron in percentages low as 0.003% will impart a hardenability factor of over 1.4; creating substantial but unpredictable hardness in the resulting TMT bars.

Luben *et al*. 2003 [11] on the other hand assert that Copper and Tin, often present as residuals, influence the hot ductility and strength of steel when their content exceeds 0.4% and 0.06% respectively, influencing its subsequent cold worked and hot worked yield value.

The purpose of this research is to examine to what extent recycled steel is able to conform to the preset limit requirement and the part the recycled steel bar chemical content has to play.

2. MATERIALS AND METHODS

The yield strength of seventy two recycled steel TMT reinforcement bars of 20mm diameter from one manufacturer was determined. To do this, one bar was selected from each of the three shifts every day for 24 working days. The bars were subjected to monotonic uniaxial loading to failure in tension using a Testomatic tensile testing machine and their yield stresses were determined in accordance to US 155-2. Their chemical composition was also determined using Spectro-apparatus spark spectrometer.

The mean yield μ and the standard deviation σ were determined from the data and the frequency distribution curve plotted with the Microsoft Office Excel *XY*-chart accordingly. The cumulative distribution function $P(X \leq \chi)$ where χ is the 550Mpa limit was then calculated by determining the standard score $z = (\chi - \mu)/\sigma$ and use of the standard normal distribution tables. Thus $P(X \geq \chi) = 1 - P(X \leq \chi)$ where χ is the random variable (yield strength) was determined.

The yield strengths for samples above 550Mpa were also plotted against their Carbon, Manganese and Boron content and the lines of best fit inserted.

3. RESULTS

Table 1 shows the yield values of the bars while Fig. 6 shows an Excel spreadsheet plot of the corresponding frequency distribution of the steel yield values.

TABLE 1: Steel Yield (Mpa).

469	497	504	515	523	528	531	534	537	542	551	555
477	499	506	515	523	528	532	535	537	543	551	560
488	501	508	516	524	529	532	536	537	546	551	572
488	502	509	517	525	530	533	537	539	548	552	576
490	502	510	521	526	530	533	537	540	549	552	584
491	502	514	522	528	531	533	537	541	550	553	588

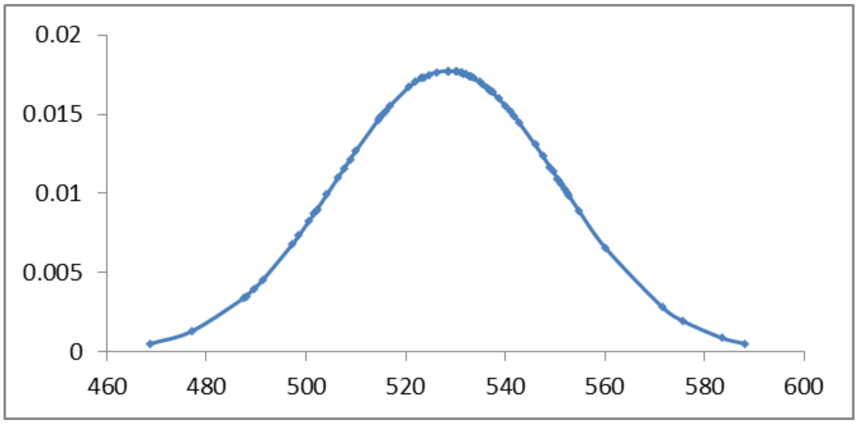

FIGURE 6: Frequency Distribution of Yield Stress.

The bell shape largely conforms to the normal distribution function with a mean value of 528Mpa and standard deviation 22.5.

The standard score $z = (\chi - \mu)/\sigma$ calculated as (550-528)/22.5 yields 0.977 which from the standard normal distribution table gives $P(X \geq \chi) = 1 - P(X \leq \chi) = 0.22$ or 22%. Thus up to 22 percent of the recycled steel samples gave rise to above the design yield stress value.

Table 2 shows the composition of the bars with yield stresses of 550Mpa and above, with the corresponding Boron, Molybdenum and Vanadium content. The Niobium and Titanium content were all below 0.001. Nitrogen was also below significant level.

TABLE 2: Yield Strength, Composition of Bars above 550Mpa.

σ_y	B	Mo	V	σ_y	B	Mo	V
550	0.0010	0.0210	0.0010	553	0.0015	0.0210	0.0010
551	0.0013	0.0203	0.0013	560	0.0018	0.0200	0.0013
551	0.0008	0.0201	0.0012	572	0.0006	0.0198	0.0010
551	0.0014	0.0207	0.0011	576	0.0021	0.0210	0.0010
552	0.0022	0.0214	0.0013	584	0.0022	0.0215	0.0021
552	0.0018	0.0240	0.0010	588	0.0027	0.0019	0.0010
558	0.0018	0.0184	0.0015	555	0.0010	0.0201	0.0008

In Fig. 7, the value of the Carbon, Manganese and Boron contents are plotted against the yield strengths of the bars above 550Mpa. The plot of yield strength against Boron content was as in Fig.8.

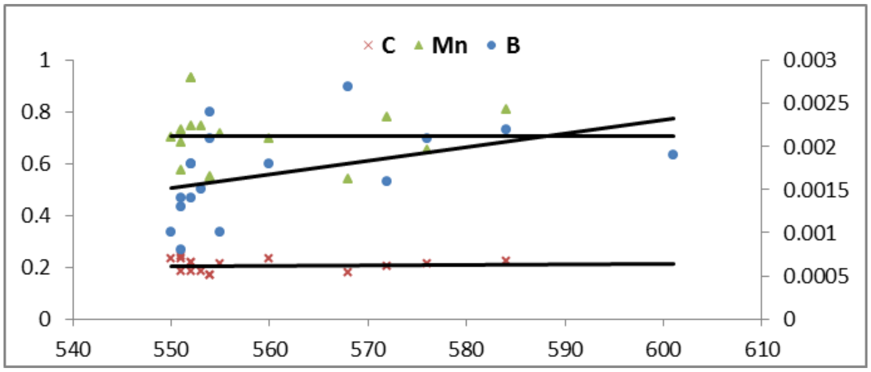

FIGURE 7: Plot of Mn and B Content against Yield.

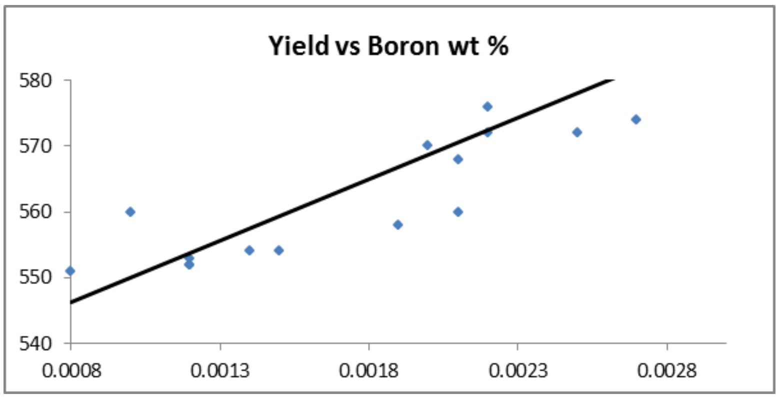

FIGURE 8: Yield against Boron Content.

4. DISCUSSION

The consistent fidelity of the steel yield values to the normal distribution function and therefore satisfaction of the normal equation:

$Y = \frac{1}{\sigma\sqrt{(2\pi)}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$ as the probability density function enables the determination of basic statistical functions and permits the determination of several important factors in the reinforcement function of the bars. Thermo-Mechanically Treated (TMT) steel bars have been developed to provide yield values of 500 to 550Mpa for longitudinal reinforcement [8]. The samples in this study show that 22% of these bars will be well above 550Mpa and the development length based on this value will not be the weaker part of the chain and failure by pull out (Fig.4) would be most likely in the event of deformation. This is the result of the unpredictable chemical composition of recycled steel.

Equation *iii)* shows that if in σ_y/τ_c, the value τ_c is held constant since the concrete type is preselected as mentioned earlier, the development length l_d will be directly proportional to the yield stress σ_y and has a similar distribution. This is also in conformity with the American Concrete Institute (ACI) development length in equation *iv)* ACI 318-08, equation 12-1.

$$l_d = \frac{1}{3.5}\left[\frac{f_y}{\lambda\sqrt{f_c'}}\right]\left[\frac{\Psi_t\Psi_e\Psi_s}{\left(\frac{C_b + K_{tr}}{d_b}\right)}\right]d_b \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . iv)$$

in which

f_y is the yield stress of the steel bar (σ_y).
f'_c the specified comprehensive strength of the concrete.
Ψ_t is takes into account the location of the bar relative to the concrete surface.
Ψ_e is a factor considering the coating on the bar (surface finish).
Ψ_e takes the size of the bar into account.
λ is the aggregate factor.

The strength and toughness obtained due to the thermo-mechanical forming of recycled steel is achieved by their chemical composition through the action of alloying and residual elements acting as solutes in iron as solvent. There are several mechanisms by which metals can be strengthened. The most outstanding among them are: transformation hardening, solid solution strengthening, precipitation hardening and grain refinement. The strengthening of metallic materials is, however, always due to the same common factor: preventing dislocation motion and/or multiplication by the interaction between the stress fields of dislocations, making them less liable to propagate [12].

In transformation hardening, a microstructure of ferrite with varying levels of martensite is formed in the steel microstructure after quenching. The varying quantities of martensite allow for differing levels of strength. The hardening process consists of heating steel so that the iron is in the face cubic centered (gamma) form, austenite, which dissolves up to 2% carbon. On suddenly cooling during quenching, the solubility of carbon is reduced and the formation of body centered cubic ferrite is not possible; instead, martensite, a super saturated body centered tetragonal form results. This features extreme hardness due to a distorted crystal structure, introducing crystal lattice defects that act as barriers to dislocation slip.

When present in steel in the range 0.001 to 0.003, Boron segregates at the austenite boundaries and inhibits grain boundary nucleation of ferrite through the segregation of $B_{23}(C,N)_6$ at the austenite grain boundaries and in this way, delays the formation of ferrite, bainite and pearlite structures. This is in preference to lower temperature transformation martensite which then increase steel yield [13]. In this way, it retards the ***γ-α*** transformation by impeding ferrite nucleation. Considering the standard practice of deoxidation with Aluminium in induction furnace melting, any Aluminium remaining not forming alumina, Al_2O_3, will also form Aluminium nitrides, reducing Nitrogen availability so that Boron remains effective. The Aluminium oxide at the same time effects grain size reduction by precipitation on grain boundary, strengthening the steel further.

In this specific study, the effect of Boron is particularly relevant considering that its presence ranges in 0.012<B<0.022 for the steel above the 550MPa (Table 2) and would produce a hardenability factor of up to 1.45 while the steel carbon content is low (below 0.25%) promoting the Boron factor since its influence is in inverse proportion to carbon content [14].

5. CONCLUSIONS AND SUGGESTIONS

Considering the manganese and carbon content of the samples, it can be affirmed that the variation of these elements in the samples studied does not give rise to substantial increased strengthening among the samples with yield stress value beyond 550MPa (Fig.7).

Boron, however, appears to play an outstanding role in fluctuating the strength of the samples with σ_y > 550 as shown by gradient of the graph in Fig. 7 and Fig. 8. This is in consonance with the Boron content of this group of samples at (0.0006<B<0.0026) and the average Carbon content being below 0.25% (Table 2). The strengthening effect of Boron up to 0.0055% on steel is not deleterious since it is not accompanied by loss of ductility [13]. The difficulty, however, arises when the Boron content is not controlled and affects the strength of the steel unpredictably as it happens with all tramp elements. Boron actually makes it hard for carbon to migrate though martensite and makes the formation of martensite easier [14]. Fig.8 correspondingly shows an increase in strength with the growing Boron content of the samples with σ_y>550 and consequent elevation of development length as in accordance to equation (*iii).*

Boron enters steel from Boron-containing scrap in which it is sometimes used in the range of 10 to 30 ppm for steel hardenability purposes, from furnace linings or from boron-containing ferrosilicon [15]. Ferro-silicon and other additives also sometimes contain Boron as residual element. The principal source of Boron in the induction furnace steel recycling practice however is the boric acid binding of the induction furnace crucible and ladle linings. An acid ramming mass is generally used in the induction furnace relining in the steel recycling industry. The silicon dioxide (SiO_2) is bound with boric acid (H_2BO_3) and is often factory pre-mixed. By adding small amounts of boric acid or boron oxide, the melting point of the silica is lowered, creating a borosilicate glass which cements the lining together. Boric oxide (B_2O_3) is reduced by silicon (and carbon at high temperature) and Boron is dissolved in the liquid iron [12]. This, however, is a ready source of up to about 0.0028%B [16].

Besides the use of low Boron containing scrap input to reduce it from the source which is not very practicable, results of a recent research confirm that sodium carbonate (Na_2CO_3) addition on an industrial basis can efficiently remove Boron from liquid iron [17]. Injection of about 100Kg/ton would virtually remove all Boron from liquid iron (Fig. 9). Pressed sodium oxide or Na_2O flux briquettes have also been added to steel in laboratory tests with some success in controlling the effect of Boron by removing it as slag.

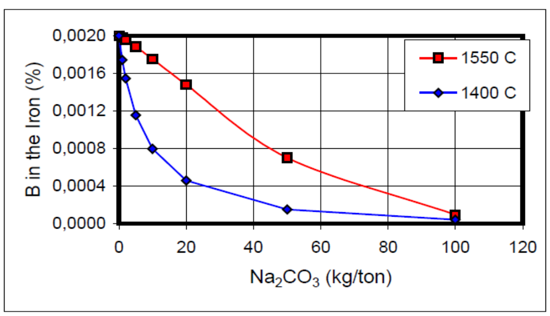

FIGURE 9: Effect of Na_2O_3 on B in Liquid Iron [23].

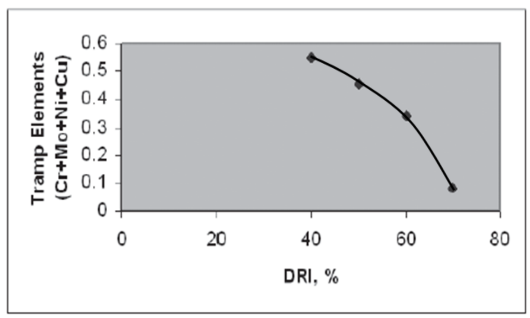

FIGURE 10: Effect of DRI on tramp element [22].

Additionally, since some of the Boron comes into steel though boric acid binder, replacing it with the alterative calcium aluminate cement would go a long way towards the reduction and control of the Boron content in induction furnace made steel[18].

The use direct reduced iron (DRI) or hard briquetted iron (HBI) pellets to dilute the effects of the residuals has been adopted in many melting shops worldwide [19]. Fig.10 shows the effect of the varying percentages of direct reduced iron supplementation on the ultimate tramp element content in steel. It actually suggests that the dilution values in scrap melting are meaningful after 40% DRI addition. Gigure et al [20] had asserted this in an earlier publication in 1996. The dilution effect is due to the fact that DRI inherently contains low amounts of tramp elements and sulphur.

It can be argued, however, that even with DRI sweetening, the ultimate result will be the accumulation of tramp elements albeit at a reduced pace. As long as scrap is still recycled, the eventual removal of the elements is still essential. The effects of the tramp elements: Arsenic, Bismuth, Cadmium, Antimony, Tellurium and Zinc can be reduced or neutralized with the addition of Cerium. The amount of Cerium necessary to counteract their harmful effects depends on the sum of all the tramp elements present although typically, about 0.01% Ce is sufficient [21]. It may be added along with traditional ferromanganese (FeSiMg).

Of great importance too is the sorting process prior to the melting of scrap. The quality of scrap in Uganda has gone down so much owing to the low supply and the growing demand that practically all kinds of inappropriate scrap are on the market. The employment of specialized scrap dealing and sorting would enable the quality of scrap to be classed so that upon purchase, the average composition of the scrap is known.

X-ray Fluorescence (XRF) analysis is widely used for scrap metal sorting and recycling by measuring the key elements in ranges of metal alloys such as stainless, tool and low alloy steels, nickel, titanium, copper, cobalt and aluminium alloys usually with hand held equipment usable at the scrap source. These tools enable the dealer to group scrap types in accordance to their elemental composition. This is a key detail in the making of quality steel and for as long as the quality of scrap keeps reducing as the availability drops, no other viable solution is available. Only a known input produces a known output.

All these measures evidently mean more expenditure and probable elevation of the product cost. Better chemistry, inclusion control and uniform temperature to enable the making of a better casting, however, are a prerequisite to safer and more reliable steel.

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