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Performance of Sugar Syrup and Corn Starch Binders on Properties of Thin Wall Ductile Iron

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Abstract: *Binders are important moulding sand constituents as they impact strength by creation of bonds in the sand mix. Production of Thin Wall Ductile Iron (TWDI) casting presents macroscopic and microscopic challenges using bentonite bonded moulding sand. In this study, moulding sand properties such as green, dry compressive strength and permeability of bentonite, corn starch and sugar syrup bonded silica sand were evaluated using various binder/sand formulations (6%, 9%, and 12%). TWDI samples of 3 mm thickness were then cast using best dry compression strength as the criteria for each binder type. Cast samples were subjected to macroscopic, microscopic and Vickers hardness analysis. Results showed that the sugar syrup bonded sand gave superior dry compression strength property of 650 KN/m2 at 6 % addition, as compared to corn starch and bentonite bonded sand which were 470 KN/m2 at 6 % addition and 445KN/m2 at 12% addition respectively. Cast TWDI samples showed nodularity and nodule counts of 96.2%, 611 nodules/mm2, 81.5%, 357 nodules/mm2 and 94.1%, 568 nodules/mm2 for samples cast using sugar syrup, corn starch and bentonite bonded sand respectively. Hardness value of 288 HV, 283 HV and 274 HV were observed for samples using corn starch, sugar syrup and bentonite bonded sand respectively. Dimensional inconsistency was observed in samples cast using all binder types with those cast using bentonite and corn starch bonded sand showing the highest thickness difference due to mould swelling from metallostatic pressure. This study has shown that adopting sugar syrup as an alternative binder for production of TWDI casting should be encouraged as both macroscopic and microscopic properties of cast TWDIs samples were greatly improved.*

Keywords: Thin wall ductile iron (TWDI), binder/sand formulations, moulding sand, macroscopic, microscopic properties.

1. INTRODUCTION

Binders are important constituents during moulding sand formulation stage, a binder impacts adequate strength by formation of adequate bonds within the foundry sand particles. The most widely used sand binders are bentonite clays, two types of bentonite exist: swelling bentonite which is also called sodium bentonite and non-swelling bentonite or calcium bentonite. Majority of bentonites occurring worldwide are of the calcium type [1, 2].

Ductile iron (DI) is an iron carbon alloy having structure of nodules of graphite embedded in the matrix which may be ferritic, pearlitic or ferritic-pearlitic (ductile grades), bainitic (strong and tough grades) or martenstic (strong and hard grades). It derives its name from it graphite in the form of spheroids embedded in the matrix, normally of ferritic, or pearlitic. These nodules of graphite are usually regular in shape and spherical. During DI production, magnesium (Mg) or cerium (Ce) additive enables the formation of graphite spheres in the melt which grew into nodules during cooling and solidification. Thin wall ductile irons (TWDIs) are DI profiles with thickness < 4 mm [3]; they are used mainly in automotive part manufacture.

It is imperative that melts for casting TWDIs components possess adequate fluidity to avoid filling related defects such as cold shuts, therefore temperatures reaching 1350 – 1450^{0}C are usually adopted for proper mould filling. However, at this temperature range, the thermal behaviour of bentonite clay in foundry sand poses a threat, firstly by gas evolution which causes defects and environmental pollution arising from harmful emissions. Secondly, by the depletion of the bonding agent which consequently reduces the dry and hot compressive strength of mould in contact with the molten metal during pouring, causing defects such as dimensional inaccuracy and poor surface finish? This high temperature heat treats the moulding sand from temperature ranging from room to the temperature of the molten metal and the bonding agent in the sand becomes inactive at such elevated temperatures [4]. These negative effects are more evident when casting thin wall sections.

Bentonite bonded sand evolve water vapour which is pushed into the solidifying metal, the water vapour undergoes decomposition in reaction with the metal. Oxygen causes decomposition and oxidation of alloying elements at the surface layer result in the surface defect while hydrogen dissolves in the liquid metal, this inducing hydrogen embrittlement [5]. The hydrogen absorbed causes low ductility by the formation of vermicular and non-nodular graphite particles alongside the nodule particles in the DI. Consequently, nodularity and nodule count reduces, also hydrogen forms cracks initiation at the grain boundaries.

Lastly in recent past, the cost of bentonite clay has risen due to its increased demand as drilling mud for crude oil exploration. These have necessitated the need to investigate other alternative binder sources to determine their suitability in casting TWDIs, so as to encourage our local foundries remain in production.

In the study of by [6], systematic finite element analysis was carried out to investigate the different binder effects namely clay, molasses and oil in the cooling of aluminium alloy during sand casting, it was observed that the mould materials controlled smooth, uniform and complete filling of the cavity by the molten metal. Computer aided design (CAD) model was generated using solid works and a fluid flow analysis was done accordingly to verify the effects. Simulation parameters and boundary conditions were extracted from an actual experimental condition, the experiments showed that clay was the best binder where cooling is more rapid.

In the study by [7], the effects of bentonite, cassava starch and yam starch binders on foundry sand were investigated. The three binders were applied separately to River Niger bank silica sand in different proportions. The effects of these various additions on foundry moulding sand were analysed by conducting moulding property tests. The results showed that bentonite had better binding characteristics as compared to cassava starch and yam starch. The green compressive strength of the three binder's increases as the percentage binder additions increased. The researchers in [8] investigated the suitability of blackstrap molasses as a core binder used in non-ferrous sand casting. Various core mixture samples were made with molasses varying from 1-5 %, soybean oil 1- 3 % and Chalawa sand the balance. The physical properties of the samples were determined via standard procedure. Using the optimum mixture, a proto-type aluminium –silicon casting was made. The result revealed that the core had good collapsibility and adequate surface finish of the internal cavity of the cast. Also adopting economically cheaper and environmentally friendly organic core binder from locally available raw material for industries was better alternative as against poisonous and expensive resinous core binders. In [5] investigation on the formation of gaseous atmosphere in a molten cast iron was studied. It was found that as a result of the cast iron contact with water vapour released from the sand, a significant amount of hydrogen was evolved, thus inducing hydrogen embrittlement. The researchers in [9], investigated the suitability of some local binders namely bentonite, cassava starch and rubber latex on microstructural and mechanical properties of sand cast grey cast iron. It was observed that castings from bentonite bonded sand gave the highest hardness value, followed by cassava and rubber latex bonded sand respectively. Also moulds bonded with bentonite and cassava starch favoured the production of grey iron microstructure, however this was not the case for the rubber latex bonded sand where dimensional inaccuracy resulting from mould expansion and porosity was observed during solidification.

In [10], a study on thermal stability of bentonites in foundry moulding sand was conducted. Their result showed that the deterioration temperatures of sodium and calcium bentonite are 1180°F and 600°F respectively.

This study is therefore aimed at investigating the suitability of alternative binders sources such as sugar syrup and corn starch on moulding sand properties using various moulding sand/binder formulations in comparison with currently used bentonite binder and also the macroscopic, microscopic and hardness properties of 3 mm TWDI cast using silica sand bonded with these binders.

2. METHODOLOGY

2.1 Materials

Corn starch was sourced from a corn starch manufacturer in Lagos State, silica sand was sourced from Ifo in Ogun State of Nigeria. The sugar syrup was made using sugar and water, while the bentonite (sodium Na-based) was also sourced from Ifo in Ogun State. The study was carried out at the Foundry Laboratory of Nigerian Machine Tools Limited, Oshogbo, Osun State, Nigeria. The silica sand particle size was between (250-300 microns). Charge materials consisted of cold rolled close annealed (CRCA) steel scrap, shell coke, ferrosilicon alloy. Ferrosilicon magnesium alloy was used for treatment after melting. Chemical compositions of CRCA steel scrap, ferrosilicon and ferrosilicon magnesium alloy are shown in Tables 1, 2 and 3 respectively.

Table 1: Chemical composition of cold rolled close annealed (CRCA) steel scrap

Element	C	S	Mn	P	Fe
wt.%	0.05	0.03	0.3	0.03	96.62

Table 2: Chemical composition of Ferrosilicon Alloy (FeSi)

Element	Si	Al	C	S	P	Fe
wt.%	70	0.31	0.0032	0.001	0.001	29.68

Table 3: Chemical composition of Ferrosilicon Magnesium Alloy (FeSiMg)

Element	Mg	Si	Ca	RE	Al	Fe
wt.%	7.5	44.5	2.02	0.8	< 0.7	44.47

2.2 Sand/binder Formulations and Moulding Sand Property Testing

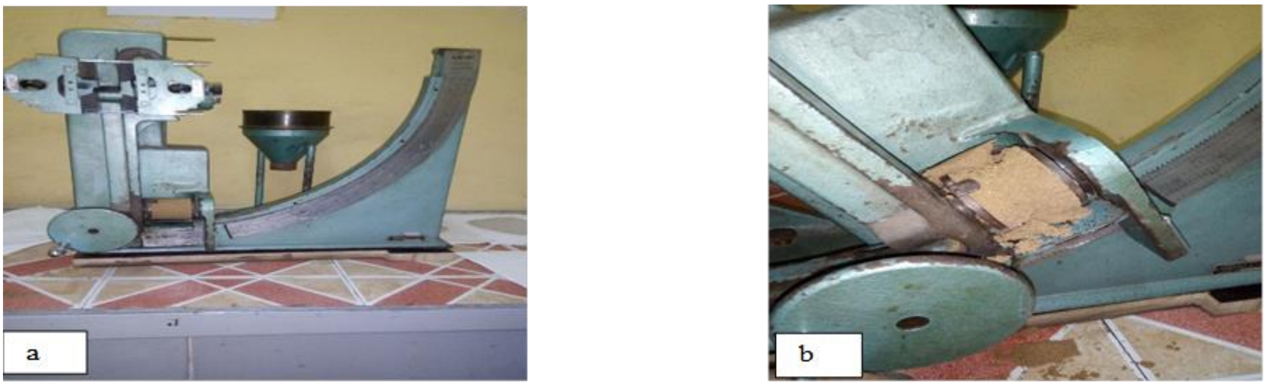
Sand recipes were prepared using different binders (corn starch and sugar syrup) while bentonite binder formed the control sample for comparison. Sand mixtures weighing 350g were prepared by mixing of dry silica sand with different binders of various weight percent's (6, 9, and 12%) respectively and 4% moisture content milled in a Ridsdale-dietert laboratory muller for 3 mins. This procedure was done for bentonite clay, corn starch and sugar syrup using the varying quantities of binders for different sand/binder formulations as shown in Table 4. Test piece 50mm in diameter and 50mm height as shown in Figure 1 was prepared for green compression, dry compression and permeability tests for each binder by weighing 150g of each sand recipe transferred into Ridsdale-Dietert Metric Standard Rammer to ram it into shape as shown Figure 2. The test piece was stripped using strip block, removed carefully and tested for green compression using Ridsdale -Dietert Universal Sand Strength Machine (Figures 3a and 3b), the machine reading was thereafter recorded. The dry compression samples were placed in an oven at 150^{0}C for 10mins before being placed on the dry compression head of the universal sand strength machine and readings were recorded. The same method was used for the permeability test but the test piece was stripped and not removed from the cylinder then inverted on the Ridsdale – Dietert Permeability Meter, the moveable knob was adjusted to firmly fit the cylinder on to the meter, the pressure knob was turned on followed by the power button of the meter and the reading (permeability) was taking on the big orifice dial.

Table 4: Constituent Compositions of Sand Binder Formulations.

Constituents	Sand (g)	Binder (g)	Water (ml)
6 % Binder	315	21	14
9 % Binder	304.5	31.5	14
12 % Binder	294	42	14

Figure 1: Test piece for mould property analysis

Figure 2: Ramming of Sand/Binder Formulations using Ridsdale Rammer



Figures 3a and 3b: Green Compression Testing using Ridsdale Sand Compression Tester

2.3 Casting of TWDI samples

Using a wooden pattern of dimension 3 x 150 x 150 mm, moulds were prepared using standard mould making specifications as outlined in ASTM E2349-19. Melting of the charge materials shown on Table 5 was done in a 250 kg capacity Induction furnace. Castings were produced using the industry standard melt charge calculation. The melt was superheated to 1520^{0}C to ensure complete mould filling in the thin walled sections. The superheated melt was poured into a preheated ladle for magnesium treatment with FeSiMg alloy using an open ladle sandwich treatment method. Two step inoculation process was done for optimum nodule properties using 0.1-0.2% FeSi before samples were cast into sand moulds prepared using the various binder/sand formulations. It is important to mention at this juncture that castings were made using the best binder/ sand formulation for dry compression strength for each binder type.

Table 5: Chemical Composition of Charge Materials

Charge	Quantity (Kg)	Charge (%)	C	Si	Mn	S	P
Cold Rolled Close Annealed (CRCA) Steel Scrap	152.5	61	0.031	-	0.25	0.005	0.001
Returns (DI)	85	34	1.19	0.88	0.02	-	--
Shell coke	10	4	2.40	-	-	-	-
FeSi	2.5	1	-	0.72			
Total	250	100	3.62	1.6	0.27	0.005	0.001

Figure 4: Cast TWDI samples in binder/ sand formulations

2.4 Macrostructural Examination

Cast TWDI samples were examined with the naked eyes for detection of possible casting defects, changes in thickness and colour. The cast thickness was determined by using a venier caliper.

2.5 Microstructural Analysis

Samples were cut, ground and polished for microstructural examination according to specifications outlined in ASTM E3 for metallographic analysis. The prepared samples were then viewed using an optical metallurgical microscope in their unetched and etched conditions; the etchant used was 2% Nital solution. Nodularity (Equation 1) and nodule count was estimated using specifications outlined in ASTM A247 and E407 standard procedures.

$$\text{Nodularity} = \frac{Number\ (area) of\ accepted\ graphite\ particles}{Number\ (area) of\ all\ graphite\ particles} \times 100 \quad (1)$$

Nodule count (graphite nodules/mm^2) is the quantity of nodules per square millimeters on a polished surface examined at X100 magnification.

2.6 Hardness Analysis

This analysis was carried out on the Wolpert Wilson Instrument Universal Vickers Hardness Tester, Model number: 930N located at Midwal Engineering, cast samples were cut from moulds of each binder of optimum formulation and the surface smoothened by grinding on emery paper. The test was carried out using specification outlined in ASTM E92 standard with a scale of HV5 (5kg force).

2.7 Spectrometric Analysis

The chemical composition of the cast TWDI samples was determined via spectrometric analysis using the spectrometer as shown in Figure 5, Model: Arun Technology Polyspek Jnr with serial no: J10 at the Foundry Laboratory of Nigeria Machine Tools Limited, Osogbo, Osun State, Nigeria.

Figure 5: Spectrometer for chemical composition analysis (Machine Tools Ltd, Osogbo)

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3. RESULTS AND DISCUSSION

3.1 Binder Sand Formulations on Green Compression strength

Plots for green compression strength with percent binder/sand formulations are shown in Figure 6. This property increases with increase in binder percent in the moulding sand for all the binders formulations used. Bentonite bonded sand showed the highest values of green compression strength ranging from 42, 66 and 85 kN/m^2 for 6, 9 and 12 % binder additions respectively, but corn starch and sugar syrup gave very poor binding characteristics.to the green sand. Corn starch bonded sand gave 8, 9 and 11 kN/m^2 for 6, 9 and 12 % binder additions respectively, whereas sugar syrup which gave the lowest results was 1, 4 and 5 kN/m^2 for 6, 9 and 12 % binder additions respectively. These results show that bentonite clay has superior binding property in the green sand as compared to corn starch and sugar syrup binders.

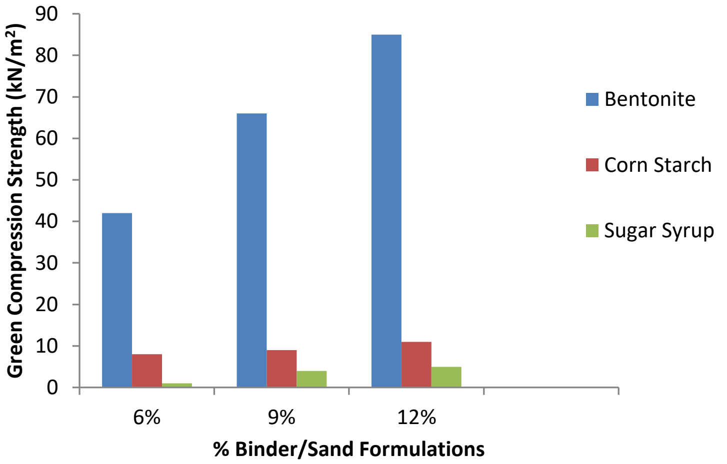

Figure 6: Chart of Green Compression Strength with %binder/Sand Formulations

3.2 Binder sand formulations on Dry Compression strength

Plots of dry compression strength with percent binder/sand formulations are shown in Figure 7. Sugar syrup binder gave the highest binding property of 650 kN/m^2 to the dry silica sand, this occurred at 6 % binder addition, 9 and 12 % sugar syrup binder additions gave 250 and 370 kN/m^2 respectively. Dry strength properties for corn starch followed with 470, 210 and 305 kN/m^2 at 6, 9 and 12 % binder additions respectively. Bentonite gave the lowest dry strength property at 6 % binder additions compared to corn starch and sugar syrup binders. It is important to mention that adequate dry compression strength is necessary to ensure dimensional integrity of the mould wall, resulting from metallostatic pressure when the mould is in contact with the molten metal. This prevents the cope and drag from expansion leading to casting defects mostly relating to dimensional inaccuracy. This low dry strength property is the problem associated with bentonite bonded sand that this study seeks to address by investigating other binder sources.

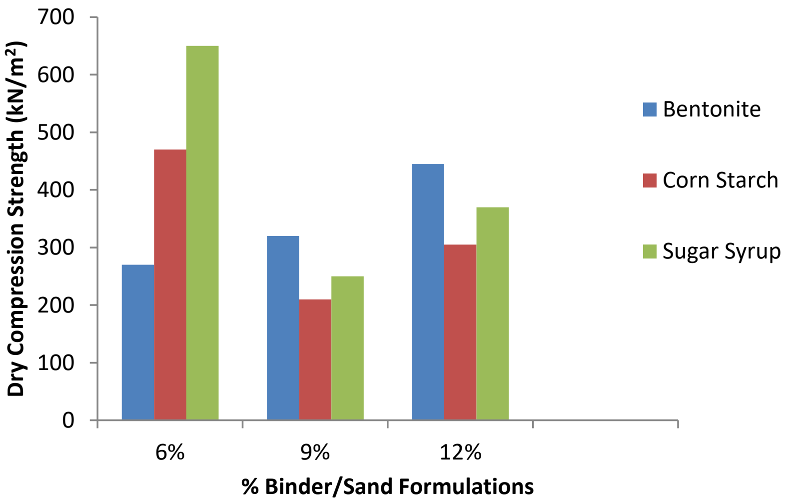

Figure 7: Chart of Dry Compression Strength with % binder/Sand Formulations

3.3 Binder sand formulations on Permeability

The chart of permeability No with percent binder/sand formulations is shown in Figure 8. The chart showed that as percent binder increases, permeability of the resulting sand mix decreases for all the binder types. The researchers in [7] and [9] also observed similar trend where permeability decreased as percent binder additions increased. Bentonite bonded sand gave the highest permeability values of 151, 146 and 128 for 6, 9 and 12% addition respectively. Corn starch bonded sand followed having values of 128, 122 and 96 for 6, 9 and 12% addition respectively. The value for 12% corn starch was the least permeability No observed for all the sand formulations used. The chart shows that bentonite bonded sand has the best permeability property compared to sugar syrup and corn starch.

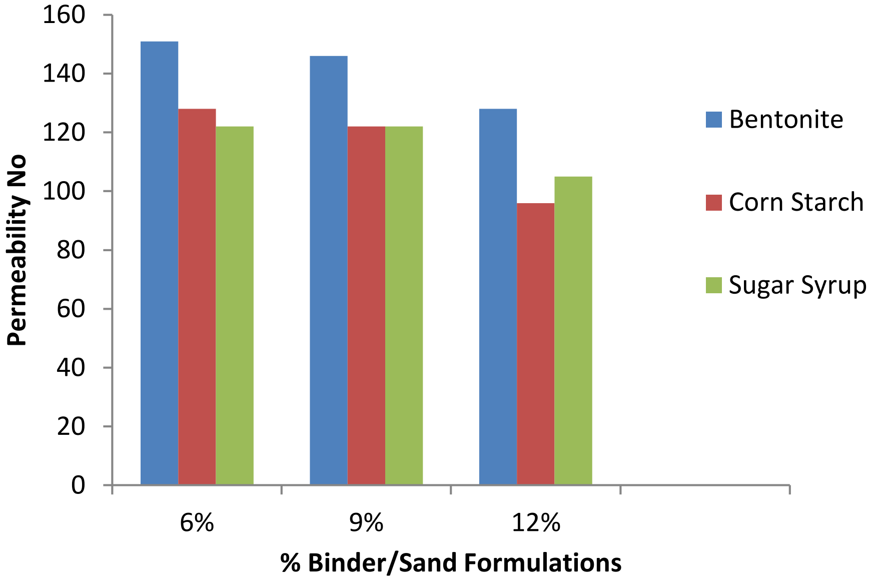

Figure 8: Chart of Permeability (No) with % binder/Sand Formulations

3.4 Effect of Binder type on Cast Thin Wall Ductile Iron

Dry compression strength was used as criteria for selection of the best binder/ sand formulation for each binder type. This property is important as melts for casting TWDI are usually in the temperature range of 1350℃ - 1420℃ thus requiring moulding sand possessing high dry compression strength to prevent expansion from metallostatic pressure imposed by the molten metal. Permeability is also an important property but other sand properties have an influence on it, also this property can be improved by proper mould venting. Based on this, and thus from Figure 6 for dry compression strength plots, 12 % bentonite, 6 % corn starch and 6 % sugar syrup bonded moulds were used for casting the 3 mm TWDI samples.

3.5 Macrostructural Examination of TWDI Castings

The macroscopic examination was done on the cast TWDI samples using the different binder types. The analysis is shown in Table 6; dimensional inconsistency was noticed as the initial 3 mm thickness used on the pattern to prepare the mould was not the final thickness on the cast components. Final thickness for castings using bentonite and corn starch bonded moulds significantly increased from 3 to 3.8 and 4.0 mm respectively whereas that of sugar syrup bonded mould increased from 3 to 3.2 mm thickness implying that the sugar syrup had minimum thickness difference as bonding property is best when in contact with the melt than bentonite and corn starch binders. Apart from the cast sample thickness, there were no defects detected and neither was there any colour change in all the TWDI samples cast using the different binders.

Table 6: Macro-examination results using the various binder types

Binder types	Colour change	Thickness (mm)	Pattern dimension (mm)	Cast defect
Bentonite	None	3.8	3	None
Sugar Syrup	None	3.2	3	None
Corn Starch	None	4.0	3	None

3.6 Chemical composition of cast TWDI sample

The chemical composition of the TWDI melt before casting and also the chemical composition of the samples cast in various binder types is shown in Table 7. This is important to determine if there is any binder/melt reaction that can be deleterious to some elements necessary for formation of optimum graphite nodule characteristics. Gases produced during casting are dissolved into the melt which can affect ductility, nodule count and nodularity of the cast component as impaired nodule particles such as compacted and chunky graphite particles. After melt treatment, residual magnesium (Mg) should be in the range of 0.03-0.05 wt. % when high purity iron, carbon and silicon are used to produce the base cast iron. This implies that the least residual magnesium of 0.03% must be present in the casting as at the time it finally solidifies, so that it can sustain optimum nodule formation in the casting [11]. Samples cast using sugar syrup bonded sand gave 0.055% residual magnesium, so this should sustain optimum graphite nodule formation, bentonite bonded sand gave 0.027%, which is very close to 0.03% whereas corn starch bonded sand gave 0.021% which is relatively low compared to the other binders and may not sustain adequate graphite nodule characteristics.

Table 7: Chemical composition of TWDI melt and TWDI samples with binder types

Samples	Fe	C	Si	P	S	Mg
TWDI before pouring	93.94	3.50	2.30	< 0.005	< 0.002	0.059
Bentonite	93.75	2.80	2.79	< 0.005	< 0.002	0.027
Sugar syrup	93.68	3.41	2.37	< 0.005	< 0.002	0.055
Corn starch	93.63	2.82	2.90	< 0.005	< 0.002	0.021

3.7 Binder types on Hardness of Cast TWDI samples

The chart of Vickers hardness (HV) versus binder types is shown in Figure 9. The values were the average of three results taken for each binder type. The samples cast using corn starch bonded sand gave the highest hardness value of 288 HV, followed by that of sugar syrup and bentonite, where castings gave 283 and 274 HV respectively.

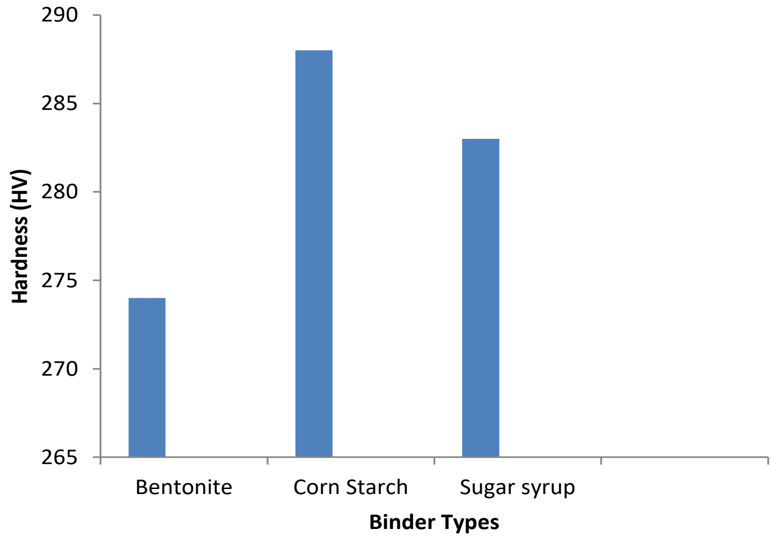

Figure 9: Hardness of cast TWDI samples with Binder Types

3.8 Binder types on Microstructure of Cast TWDI samples

Final microstructure of cast 4 mm TWDI samples were composed of bull eyed graphite nodules, ferrite, pearlite and carbide phases. Microstructure of samples cast using bentonite, sugar syrup and corn starch bonded silica sand are shown in Figures 10, 11 and 12 respectively. Carbide precipitates which is a metastable transformation product was evident in TWDI samples cast in corn starch bonded sand. Samples cast in sugar syrup bonded sand showed superior structure with reduced carbide precipitation though carbide precipitation is seen sparingly in the microstructure of samples cast using bentonite bonded sand (Figure 10). Also from Table 7, samples cast using sugar syrup bonded sand have the highest amount of residual magnesium of 0.055, it is expected that graphite nodule characteristics would be optimum which is the case. Carbide precipitation in TWDI cast using corn starch bonded sand as seen in Figure 12 consequently led to the high hardness value of 288 HV as seen in Figure 9.

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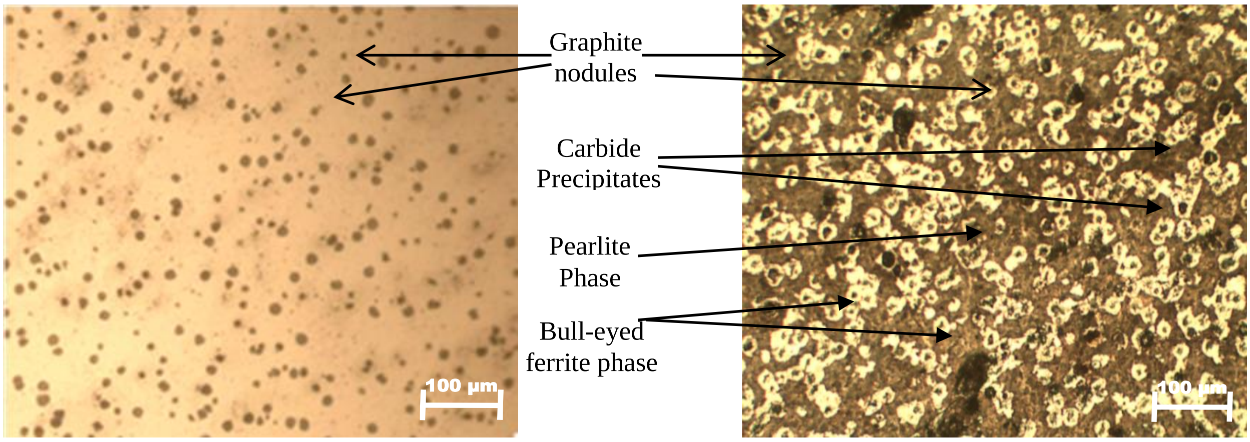

Figure 10: Micrographs of TWDI cast in Bentonite bonded sand (a) Unetched (b) Etched

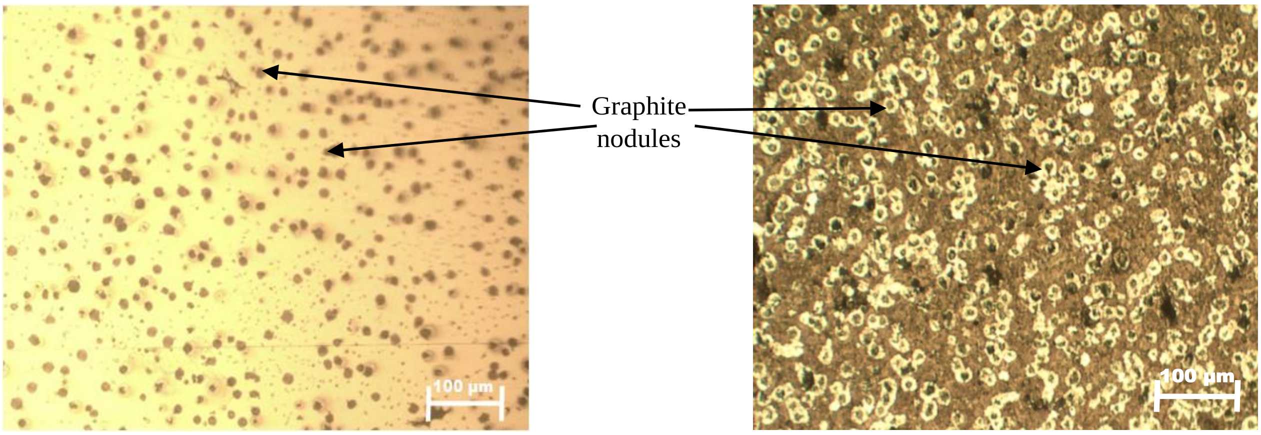

Figure 11: Micrographs of TWDI cast in Sugar syrup bonded sand (a) Unetched (b) Etched

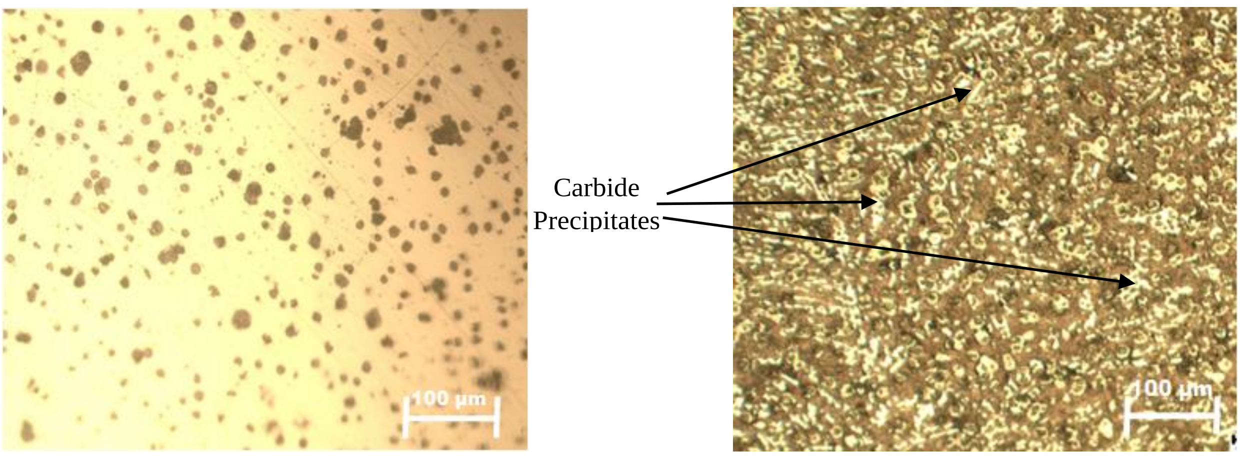

Figure 12: Micrographs of TWDI cast in Corn Starch bonded sand (a) Unetched (b) Etched

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3.9 Binder types on Nodularity and Nodule Count of Cast TWDI samples

The plot for nodularity with binder type for cast TWDI samples is shown in Figure 13. Nodularity estimate for TWDIs cast using bentonite and sugar syrup bonded sand were 94.1% and 96.2% respectively, whereas that of corn starch bonded sand gave 81.5%.

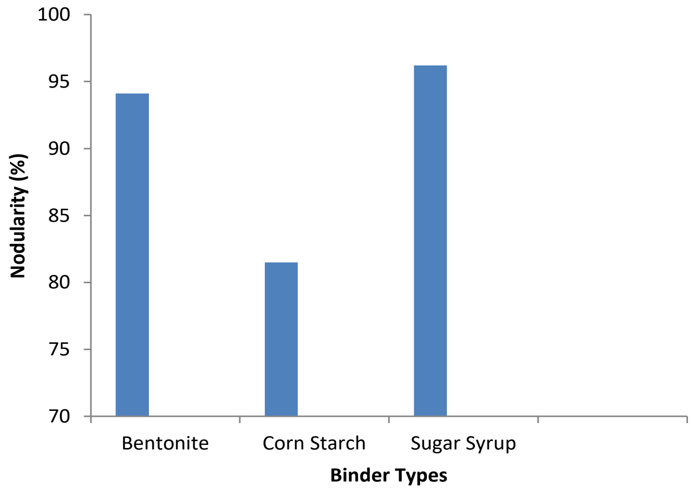

Figure 13: Nodularity (%) of cast TWDI samples with Binder Types

The nodule count with binder type chart for cast TWDI samples is shown in Figure 14. Casting from sugar syrup gave bonded sand gave the highest value of 611 nodules/mm^2, followed by those of bentonite bonded sand which gave 568 nodules/mm^2, whereas that of corn starch gave a relatively low value of 357 nodules/mm^2. This shows that bentonite and sugar syrup are suitable for formation of good nodule characteristics in cast 4 mm TWDI whereas corn starch is not as suitable. This trend is expected as is seen from the amount of residual magnesium in Table 7, where that for sugar syrup is the highest, followed by bentonite, whereas corn starch has the least amount of residual magnesium.

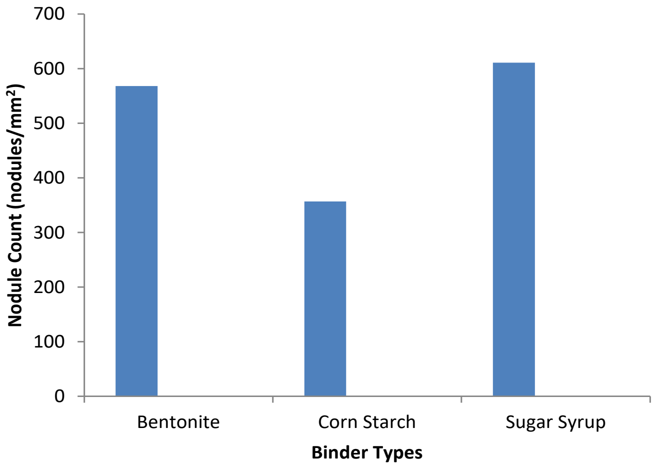

Figure 14: Nodule count/mm^2 of cast TWDI samples with Binder Types

4. CONCLUSIONS

This study has shown that sugar syrup is a suitable alternative binder in comparison to bentonite for casting TWDI components. Dry compression strength which is the important property that determines the integrity of the mould when in contact with the TWDI melt is highest in sugar syrup bonded silica sand moulds giving the value of 650 kN/m2 at 6 % binder addition. This indicates that using 6% binder addition, the binding property of sugar syrup in the sand mould is not deteriorated at the casting temperature. When comparing their green compression strengths, that of bentonite bonded sand is significantly higher than that of sugar syrup bonded sand. Permeability properties are also comparable to that of bentonite. Hardness of castings from sugar syrup bonded sand which gave 283 HV is higher than that of bentonite bonded sand which is 274 HV. Microstructure of casting from bentonite and sugar syrup bonded silica sand showed little or no carbide precipitation, this structure is desirable than that of the corn starch bonded sand where significant volume of carbide precipitation is evident. Also, nodularity estimates for TWDI castings from bentonite and sugar syrup bonded sand are adequate reaching 94.1% and 96.2% respectively. Nodule count estimate is higher in sugar syrup bonded sand than that obtained for bentonite bonded sand, whereas that of corn starch gave the lowest value of 357 nodules/mm2.

This study has also shown that corn starch is not very suitable compared to currently adopted bentonite binder for casting TWDI components. Microstructure of cast TWDI samples using corn starch bonded sand yielded large volumes of carbide precipitates, although corn starch bonded mould showed comparably good permeability properties. The amount of residual magnesium needed to sustain adequate nodule characteristics is low in samples cast using corn starch bonded sand compared to the other two binders used.

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