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PERFORMANCE OF KAOLIN AND CASSAVASTARCH AS REPLACEMENTS FOR BENTONITE IN MOULDING SAND USED IN THIN WALL DUCTILE IRON CASTINGS

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ABSTRACT
Thin Wall Ductile Iron (TWDI) casting presents macroscopic and microscopic challenges using bentonite bonded moulding sand. In this study, moulding properties of bentonite, cassava starch and kaolin bonded silica sand were evaluated using various binder/sand formulations (6%, 9%, and 12%). TWDI samples of 3 mm thickness were cast using dry compression strength as criteria for each binder type. Cast samples were subjected to macroscopic, microscopic and Vickers hardness analysis. Kaolin bonded sand gave superior dry strength property of 650 KN/m^{2}at 6 % addition. Samples showed nodularity and nodule counts of 96.2%, 587 nodules/mm^2, 76.2%, 61 nodules/mm^2 and 96.5%, 985 nodules/mm^2 using kaolin, cassava starch and bentonite bonded sand respectively. Thickness deviations were observed in all samples, bentonite bonded samples being most significant. This study has shown that adopting kaolin as alternative binder for production of TWDI casting should be encouraged as properties of cast TWDIs samples were greatly improved.

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

1. INTRODUCTION

Over 70% of all metal castings are produced via a sand casting process; sand casting is a metal casting process characterized by using sand as the mould material. Insand casting is one of the most popular and simplest types of casting. Not only does this method allow manufacturers to create products at a low cost, other benefits such as reusability and casting of complex shapes are possible. In addition to the sand, a suitable bonding agent (called binders majorly clay) is mixed with the sand, and then the mixture is moistened with water to develop strength and plasticity. And make the aggregate suitable for moulding and also enable it to retain its shape as mould cavity consequently making binder's important constituents during moulding sand formulation stage. Binders should be added in optimum quantity as they reduce refractories and permeability.

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 martensitic (strong and hard grades). It derives its name from its graphite in the form of spheroids/nodules. These nodules of graphite are usually regular in shape and spherical. The matrix of DI can be varied from a soft and ductile ferritic structure, through harder and high strength pearlitic structures to hard, higher and comparatively tough tempered martensitic or bainitic structures. Thus, a wide range of combinations of strength and ductility can be achieved. General engineering grades of DI commonly have the structures which are ferritic,

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ferritic/pearlitic or pearlitic [1]. 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. The usage of DI has increased drastically since the middle of the 1960`s when the beneficial properties of DI started to be widely known, high castability and surface hardenability, good machining potential, a relatively high strength to weight ratio together with good vibration damping. DI materials replaced grey and malleable cast iron in many products, between 1965 and 2010 the worldwide production of DI increased with 13 fold, from 1.5 million tonnes/year to 20million tonnes/year [2].

Thin wall ductile irons (TWDIs) are DI profiles with thickness < 4 mm [3], they are used mainly in automotive part manufacture. In casting TWDI parts, the molten metal pouring temperature reaches 1350 – 1450^{0}C, this is necessary to achieve adequate fluidity that enables proper mould filling. However at this temperature range, the thermal behaviour relating to dry and hot compressive strength of bentonite clay in foundry sand poses a threat, firstly by gas evolution which causes defects and environmental pollution arising from harmful emissions, and secondly by the depletion of the bonding agent in the sand in contact with the molten metal during pouring. This also leads to defects such as dimensional inaccuracy and poor surface finish, arising mostly from metallostatic pressure of the liquid metal and insufficient strength of the mould to retain the exact shape of mould cavity. 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 resulting in surface defects while hydrogen dissolves in the liquid metal, this inducing hydrogen embrittlement and also crack initiation at the grain boundaries [4]. The hydrogen absorbed causes low ductility by the formation of vermicular and non-nodular graphite particles alongside the nodule particles in the ductile iron, consequently reducing modularity and nodule count [5].

In addition, the cost of bentonite clay in recent times has risen as a result of its increased demand in crude oil exploration activities, therefore the need to source for other alternative binders that can meet the properties required in cast TWDIs, so as to encourage our local foundries to remain in production.

The researchers in [6] investigated the effects of bentonite and cassava starch binders on foundry sand by conducting various moulding property tests after their incorporation into the sand. The results showed that bentonite had better binding characteristics than cassava starch but a mixture of both in equal proportions gave a range of excellent mould properties that could be exploited in making moulds for different weights of castings. Permeability for the two binders decreased as the quantity of binder increased. The researchers in [7] investigated the effects of bentonite, cassava starch and yam starch binders on foundry sand. The three binders were applied separately to River Niger bank silica sand in different proportions. The results showed that green compressive strength and mouldability of the three binders's increased as the percentage binder additions increased. In the study of [8], the effects of polyurethane no bake binder sand moulds on collapsibility and surface finish of grey iron castings was carried out. ANOVA and regression analysis was performed to establish the relation between factors and responses and a good correlation was observed. Also the amount of binder to be added in reclaimed sand may be smaller than that added in new sand, the studies showed that sulphur is the primary factor that causes graphite degeneration in metal–mould interface [5] and [9]**.** The researchers in [1] adopted finite element analysis to investigate different binder effects in cooling of sand cast aluminium alloy. In this study three different types of binding materials namely clay, molasses and oil were used as binding material. Bottom gating system was used for its low gas entrapment and less surface defect characteristics. Experimentation was carried out for the different binders and computational analysis was also done for selection based on cooling rate. A CAD model was generated using Solid work and a fluid flow analysis was done accordingly to verify the effects. Simulation parameters and boundary conditions were extracted from an actual experimental condition. They concluded Both the experimentation and CFD simulation shows that clay is the best binder where cooling is more rapid.The study in [10] showed the investigation on the suitability of selected local sand binders on microstructural and mechanical properties of sand cast- grey cast iron was examined. The bentonite, cassava starch, rubber latex was varied for 5wt% -11wt% fritter added to 100% silica sand of 5wt% water. Results obtained from grey casts revealed a pearlitic matrix interface, massive carbide and graphite phases. Moulds bonded with bentonite and cassava starch appeared better with average hardness value of 437 and 385 (BHN) respectively. The microstructure was seen to be dominated by majorly pearlitic matrix with little carbide which are favourable for the formation of grey cast iron which requires low chilling in the mould. The researchers in [11] investigated the thermal stability of bentonites in foundry moulding sand. 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 performance of alternative binders sources such as kaolin and cassava starch on moulding sand properties using various moulding sand/binder formulations in comparison with currently used bentonite binder and also their effects on macroscopic, microscopic and hardness properties of 3 mm TWDI cast using silica sand bonded with these binders.

2. MATERIALS AND METHODS

2.1 Materials Preparation

Silica sand used for this study was sourced from Ifo in Ogun State of Nigeria, the cassava starch was sourced from a cassava starch dealer in Lagos State, Nigeria. Kaolin clay was sourced from Jos, while the sodium (Na)-based bentonite was also sourced from Ifo in Ogun State. The study was carried out at the Foundry Laboratory of Nigerian Machine Tools Limited, Osogbo, 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 1-3 respectively.

2.2. Sand/binder Formulations and Moulding Sand Property Testing

Sand recipes were prepared using different binders (kaolin and cassava starch) 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 3mins. This procedure was done for bentonite clay, kaolin clay and cassava starch using the varying quantities of binders for different sand/binder formulations as shown in Table 6. 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 (Figure 3).

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

Table 4: Chemical composition of Bentonite (sodium based)

Constituent	SiO2	Al2O3	Fe2O3	Na2O	CaO	K2O	TiO2	MgO	LOI
Wt. %	73.2	16.95	2.12	3.66	0.77	0.76	0.32	2.22	0

Table 5: Chemical composition of Kaolin

Constituent	SiO2	Al2O3	Fe2O3	Na2O	CaO	K2O	TiO2	MgO	LOI
Wt. %	51.7	39.96	0.94	0.28	0.25	0.76	0.09	0	6.02

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.

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 procedures. Melting of the charge materials shown on Table 7was done in an250kg capacity Induction Furnace. Samples 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.

2.5 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 vernier caliper.

2.6 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.

Table 6: 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 Analusis

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

Figure 3: Green Compression Testing using Ridsdale Sand Compression Tester

Table 7: 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

Nodularity, N and nodule count were estimated using specifications outlined in ASTM A247 and E407 standard procedures.

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

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

2.7 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).

2.8 Spectrometric Analysis

The chemical composition of the cast TWDI samples was determined via spectrometric analysis using the spectrometer at the Foundry Laboratory of Nigeria Machine Tools Limited, Osogbo, Osun State, Nigeria.

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 5. This property increases with increase in binder percent in the moulding sand except for cassava bonded sand where there is a decline at 9%. 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. In the investigation carried out by researchers in [6], similar trend was also observed, that of kaolin bonded sand gave 6, 22 and 50 kN/m^2 for 6,9 and 12 % binder additions respectively whereas cassava bonded sand gave the lowest values of 6, 5 and 15 kN/m^2 for 6,9 and 12 % binder additions respectively. These results indicate that cassava starch impacts poor binding characteristics to the green sand as compared to the other binders.

Figure 4: Cast TWDI samples in binder/ sand formulations

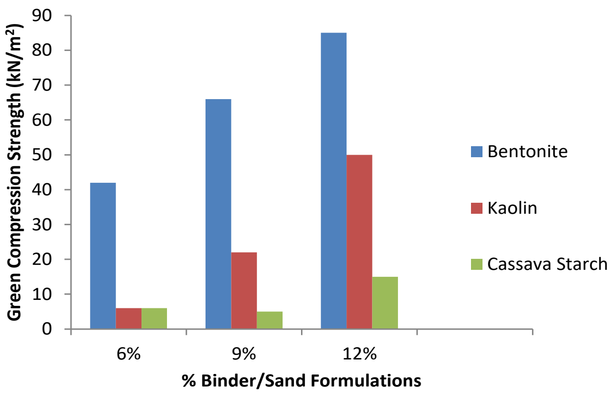


Figure 5: Green Compression Strength with %binder/Sand Formulations

3.2 Binder Sand Formulations on Dry Compression Strength

Plots of dry compression strength with percent binder/sand formulations is shown in Figure 6. Kaolin binder at all percent additions gave highest binding property to the dry sand i.e. 650, 650 and 630 kN/m^2 for 6, 9 and 12% binder additions respectively in silica sand. When the melt is poured into the mould cavity, the parts of the mould in contact with the melt become dry, resulting from the heat from the molten metal hence the name dry compressive strength. It is important to mention that adequate dry compression strength is necessary to ensure dimensional integrity of the mould wall that occurs 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. Cassava bonded sand followed with 510, 575 and 370 kN/m^2 for 6, 9 and 12% binder additions respectively. Bentonite showed the lowest binding characteristics in the sand's dry state though at 12% binder addition this property improved considerably, 270, 320 and 445 kN/m^2 at 6, 9 and 12% binder additions respectively were observed. This is actually the problem associated with bentonite bonded sand that this study seeks to address by investigating other binder sources.

3.3 Binder Sand Formulations on Permeability

The chart of the permeability with percent binder/sand formulations is shown in Figure 7. The highest permeability was observed for bentonite bonded sand, 151,146 and 128 for 6, 9 and 12 % binder additions respectively, 126, 102 and 108 were the permeability numbers for 6, 9 and 12 % kaolin binder additions and 126, 119 and 105 for 6, 9 and 12 % cassava starch binder additions. Permeability decreases as percent binder increased for all binders adopted except for 12 % kaolin where an increase is observed from 9 % kaolin addition. The researchers in [7] and [10] also observed the same trend where permeability decreased as percent binder additions increased.

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 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 though other sand characteristics have an influence on it. It can also be improved by proper mould venting. Based on this, thus from Figure 6 for dry compression strength plots, 12 % bentonite, 6 % kaolin and 9 % cassava starch bonded moulds were used for casting the 4 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 8; significant thickness deviations was noticed as the initial 3 mm thickness used for pattern making was not replicated as the final thickness on the cast components. Final thickness for castings using bentonite and cassava starch bonded moulds increased from 3 to 4.9 and 4.5 mm respectively whereas that of kaolin bonded mould increased from 3 to 3.5 mm thickness implying that kaolin had minimum thickness difference as bonding property is best when in contact with the melt than bentonite and cassava starch binders. There were no defects detected and neither was there any colour change in all the TWDI samples cast using the different binders.

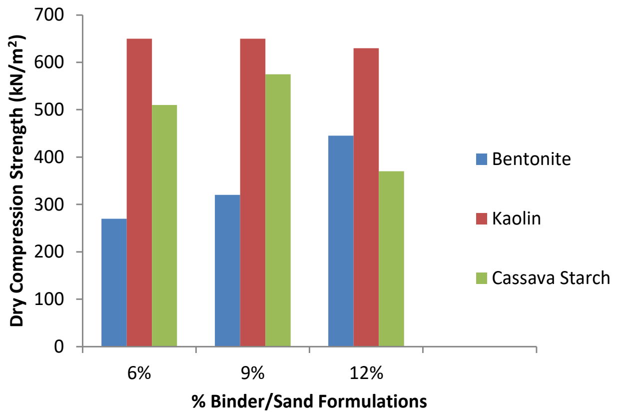


Figure 6: Dry Compression Strength with %binder/Sand Formulations

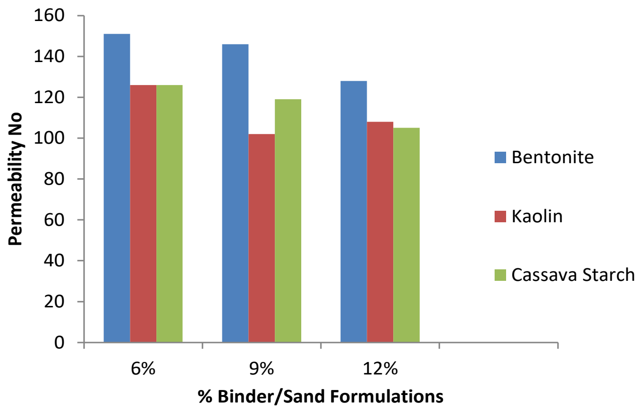


Figure 7: Permeability (No) with %binder/Sand Formulations

Table 8: Macro-examination results using the various binder types

Binder Type	Colour change	Thickness (mm)	Pattern dimension (mm)	Cast defect
Bentonite	None	4.9	3	None
Kaolin	None	3.5	3	None
Cassava Starch	None	4.5	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 9. 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 [12]. Samples cast using kaolin bonded sand 0.034% residual magnesium, so this should sustain optimum nodule formation, bentonite bonded sand gave 0.027%, which is very close to 0.03% whereas cassava starch bonded sand gave 0.017% which is low and may not sustain adequate graphite nodule characteristics.

3.7 Binder Types on Hardness of Cast TWDI Samples

The chart of Vickers hardness (HV) versus binder types is shown in Figure 8. The values were the average of three results taken for each binder type. The samples cast using bentonite, kaolin and cassava bonded sand gave standard deviations of 2.16, 3.26 and 3.55 respectively. Castings prepared using cassava starch bonded sand gave the highest hardness value of 305HV, followed by that of kaolin and bentonite, where castings gave 283 and 275 HV respectively.

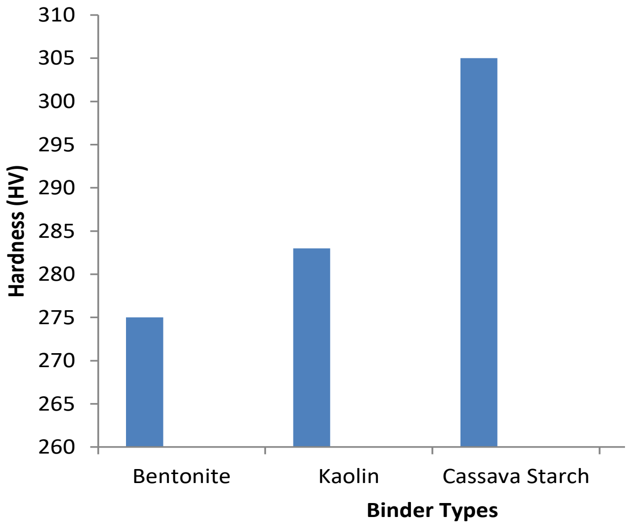


Figure 8: Hardness of cast TWDI samples with Binder Types

3.8 Binder Types on Microstructure of Cast TWDI Samples

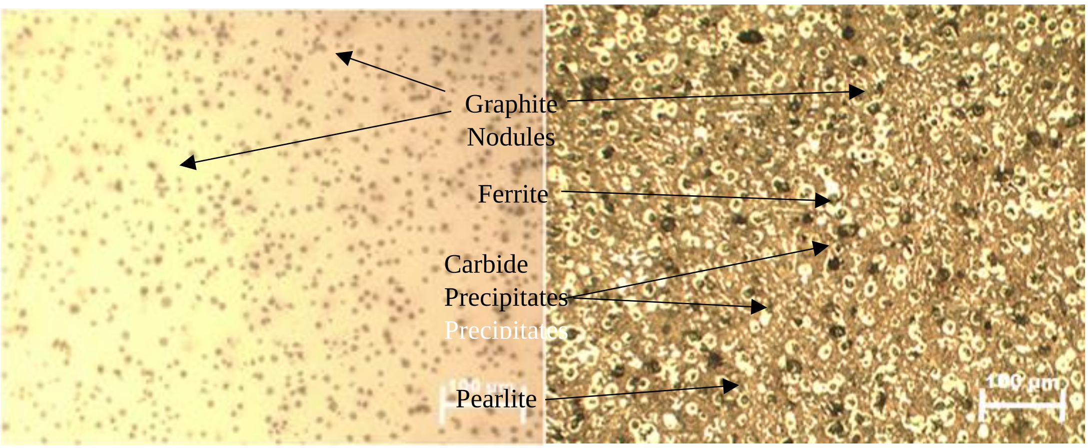
Microstructure of castings made using bentonite, kaolin and cassava starch bonded silica sand are shown in Figures 9, 10 and 11 respectively. Final microstructure of cast 4 mm TWDI samples were composed of bull eyed graphite nodules, ferrite, pearlite and carbide phases.

Carbide precipitates which is a metastable transformation product was evident in TWDI samples cast in cassava bonded sand and also in samples cast in bentonite bonded sand, though more evident in the former than the latter. Samples cast in kaolin bonded sand showed superior structure with reduced carbide precipitation.

Table 9: Chemical composition of TWDI melt and TWDI samples with binder types

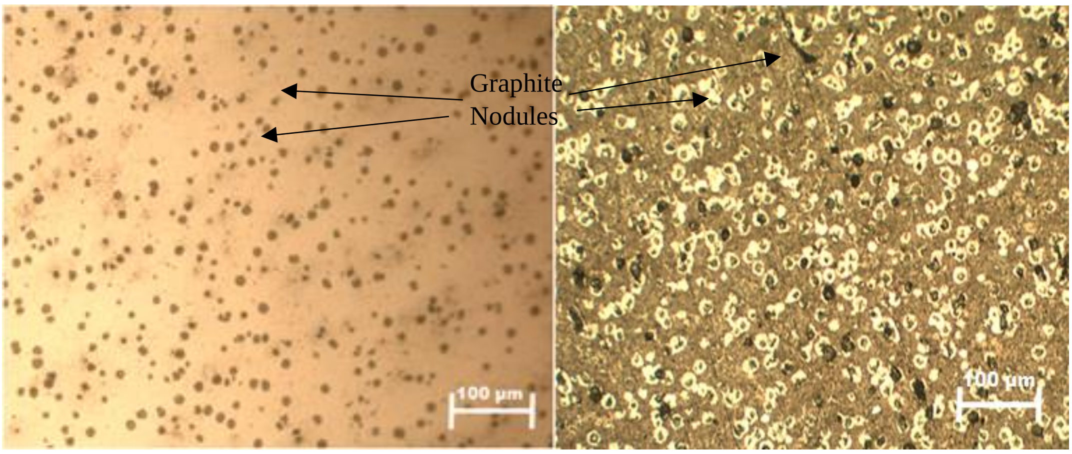
Samples	Fe	C	Si	P	S	Mg
TWDI before pouring	93.94	3.50	2.30	< 0.005	< 0.002	0.059
Bentonite	93.75	2.80	2.79	< 0.005	< 0.002	0.027
Kaolin	93.44	3.15	2.77	< 0.005	< 0.002	0.034
Cassava starch	93.73	2.77	2.85	< 0.005	< 0.002	0.017

Also from Table 8, samples cast using kaolin bonded sand have the highest amount of residual magnesium of 0.034%, it is expected that graphite nodule characteristics would be optimum. The large volume of carbide precipitation in TWDI cast using cassava bonded sand as seen in Figure 11 consequently led to the high hardness value of 305HV as seen in Figure 8.



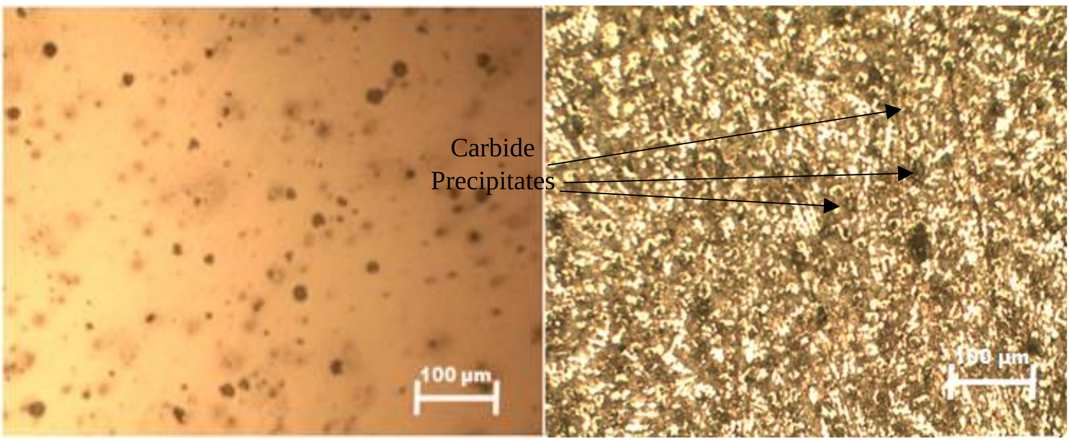
(a) (b)

Figure 9: Micrographs of TWDI cast in Bentonite bonded sand (a) Unetched (b) Etched



(a) (b)

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



(a) (b)

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

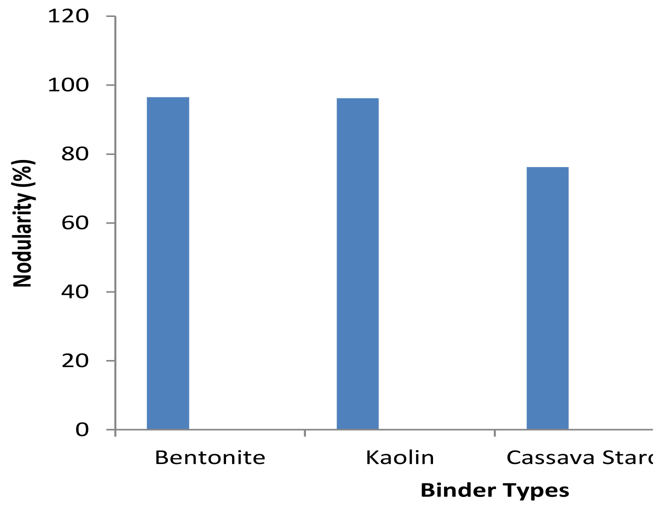


Figure 12: Nodularity (%) of cast TWDI samples with Binder Types

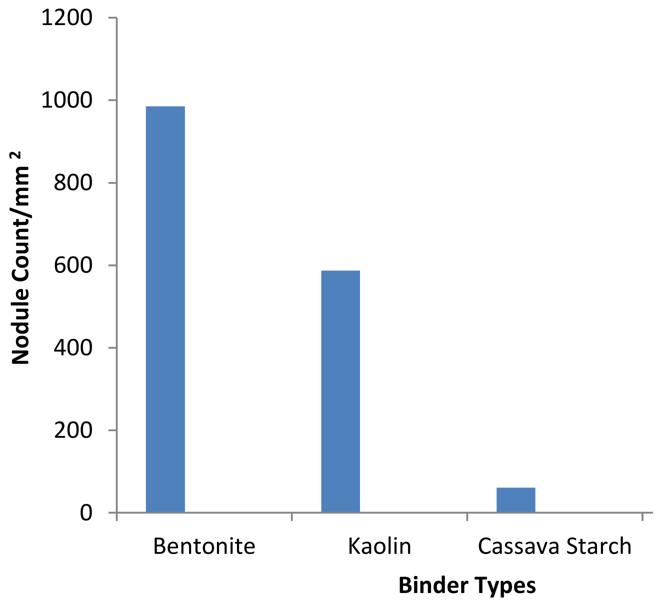


Figure 13: Nodule count/mm^2 of cast TWDI samples with Binder Types

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

The nodularity with binder type chart for cast TWDI samples is shown in Figure 12. Nodularity estimate for TWDIs cast using bentonite and kaolin bonded sand were 96.5% and 96.2% respectively, whereas that of cassava starch bonded sand gave 76.2%.

The nodule count with binder type chart for cast TWDI samples is shown in Figure 13. Casting from bentonite bonded sand gave the highest value of 985 nodules/mm^2, followed by those of kaolin bonded sand which gave 587nodules/mm^2, whereas that of cassava starch gave a very significantly low value of 61 nodules/mm^2. This shows that bentonite and kaolin are suitable for formation of good nodule characteristics in the cast 4 mm TWDI whereas cassava starch is not suitable. This trend is expected as can be seen from the amount of residual magnesium in Table 8. That for kaolin is the highest, followed by bentonite, whereas cassava starch has the least.

4. CONCLUSION

This study has shown that kaolin clay sourced from Josis a suitable alternative binder in comparison to bentonite for casting TWDI components. Dry compression strength values for kaolin bonded sand gave the highest values for all percent binder additions showing that binder properties in the moulding sand are not deteriorated at casting temperatures. Green compression strength and permeability properties are also comparable to that of bentonite. Hardness of castings from kaolin bonded sand which gave 283HV is slightly higher than that of bentonite bonded sand which is 275HV. Microstructure of casting from kaolin bonded sand showed little or no carbide precipitation, this structure is desirable than that of bentonite bonded sand where significant volume of carbide precipitation is evident. The shows that at the casting temperature, the binding properties of kaolin is better than that of bentonite in the moulding sand. Also nodularity of TWDI castings from kaolin bonded sand is almost the same as that of bentonite bonded sand i.e. 96.2% and 96.5% respectively though their nodule counts are significantly different.

This study has also shown that cassava starch is not suitable compared to currently used bentonite binder for casting TWDI components. Microstructure of cast TWDI samples using cassava bonded sand yielded large volumes of carbide precipitates, poor nodularity and nodule count ratings. Although cassava bonded mould showed comparably good dry compression strength values better than that obtained for bentonite bonded sand, binding strength at casting temperatures and amount of residual magnesium needed to sustain adequate nodule characteristics is better for bentonite bonded sand than cassava bonded sand.

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