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(54) Title: STEEL LADLE FURNACE SLAG BINDER MATERIALS AND USES THEREOF

(57) Abstract: Compositions that include a binder material and a particulate material are described. The binder material includes steel ladle furnace slag. The binder material is capable of binding the particulate material together. Uses of the compositions are also described.



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**STEEL LADLE FURNACE SLAG BINDER MATERIALS AND USES THEREOF****CROSS REFERENCE TO RELATED APPLICATIONS**

[0001] This application claims the benefit of priority of U.S. Provisional Patent Application No. 62/788,527 filed January 4, 2019, which is hereby incorporated by reference in its entirety.

**BACKGROUND OF THE INVENTION****A. Field of the Invention**

[0002] The invention generally concerns a composition that includes a binder material and particulate material. The binder material includes steel ladle furnace slag.

**B. Description of Related Art**

[0003] Solid catalysts can be agglomerates of mixed metal oxides, supported metals, metal oxides, and/or metal sulfides. These materials can have high porosity, but exhibit brittleness. By way of example, aluminum oxide pellets, (*e.g.*, corundum) when subjected to high temperature and pressure can exhibit unstable mechanical integrity causing the pellets to transform into very fine fragments in severe environments and during industrial reactions.

[0004] Different binder materials can be blended with the catalytic material and/or supported catalytic material to enhance the stability and strength of the formed catalyst. Conventional binder material includes bentonite, cement, boehmite, aluminum phosphate, alumina gel, kaolin, silica gel, pseudo-boehmite, steel slag based inorganic polymer gelling material, and the like. Steel slag has been investigated for use as binders and fillers in various compositions. By way of example Chinese Patent Nos. 104150941 and 102688764 to Zhang *et al.*, 107409847 to Li, Korean Patent Application Publication No. 20080034804 to Kim, and U.S. Patent No. 8,147,610 to Feng *et al.* describe the use of steel making slag to form cementitious binders. This steel slag suffers in that it requires complicated processing steps such as being reacted with a polymer, alkali metal oxide sol gel, or silica containing materials under hydrothermal conditions to produce a useable binder. Further, the steel slag used in these Chinese, Korean, and US publications appears to include at least 19 wt. % of iron oxide ( $\text{Fe}_2\text{O}_3$ ), which can be detrimental to catalyst reactions.

[0005] The currently available binder materials often have many defects that will degrade and impose weakness of the unused and spent catalysts. Additionally, significant concentrations of such binder materials have to be used, which increases the costs of the produced catalytic material.

**SUMMARY OF THE INVENTION**

[0006] A discovery has been made that address at least some of the aforementioned problems associated with binder materials that can be used with catalysts. The discovery is

premised on the use of steel ladle furnace slag, also referred as steel plant secondary metallurgy flat product slag (SFP). In particular, it was discovered that when steel ladle furnace slag is used as a binder for particulate matter (e.g., catalytic material), it can provide enhanced crushing strength of the bound particulate matter as compared to steel slag produced from an electric arc furnace. Without wishing to be bound by theory, it is believed that the lower content of iron oxide in the steel ladle furnace slag (e.g., less than 7 wt. %, preferably 0.1 to 7 wt. % of iron oxide as compared to other steel slags (e.g., 20 to 60 wt.% in steel slag from EAF and BOF processes) may contribute to the enhance crushing strength. The use of steel ladle furnace slag also provides utilization of low valued materials produced from the steel making industry in relatively low amounts, thereby reducing the overall costs of the binder material and the amount of binder material used to bind particulate matter together. Use of steel ladle furnace material as a binder material in the context of the present invention can provide at least one of, any combination of, or all of the following advantages: (1) sufficient strength of the bound particulate material to withstand thermal shock, rapid depressurization, and/or similar events that occur during catalytic chemical reactions on a commercial scale; (2) sufficient mechanical properties of the bound particulate material that allows the material to withstand crushing, attrition, and breakup during shipping and reactor loading; (3) production of a variety of shapes of the bound particulate material (e.g., pellets having random shapes, spheres, tablets, extrudates, rings, granules, *etc.*); and/or (4) sufficient mechanical properties of the bound particulate material to withstand various forms of stresses including thermal (*e.g.* high temperature), chemical (*e.g.*, steam, carbon formation), and mechanical (*e.g.*, pressure and mechanical failure).

**[0007]** In one aspect of the present invention, a composition can include a binder material that includes steel ladle furnace slag and a particulate material bound together with the binder material. The particulate material can be a catalyst material and/or a fertilizer material (*e.g.*, a particulate fertilizer capable of fertilizing a soil or a plant), thereby resulting in a catalyst composition or a fertilizer composition having the steel ladle furnace slag as a binder. The composition can have a horizontal crush strength of 250 daN to 500 daN, as measured by ASTM D4179. The composition can be in particulate form, have a shape (*e.g.*, a spherical shape, a ring shape, a cylindrical shape or a tablet shape), be extrudable, or any combination thereof. The composition can include steel ladle furnace slag in an amount of at least 1 wt.%, preferably at least 5 wt. %, or 1 wt. % to 60 wt. % or 5 wt. % to 25 wt. % or any value or range there between. In some aspects, the steel ladle furnace slag can include, based on the total weight of the steel ladle furnace slag: 20 wt. % to 65 wt. % calcium oxide (CaO), preferably

20 wt. % to 45 wt. % CaO, or more preferably 43 wt. % to 44 wt. % CaO; 5 wt. % to 60 wt. % aluminum oxide ( $\text{Al}_2\text{O}_3$ ), preferably 35 wt. % to 60 wt. %  $\text{Al}_2\text{O}_3$ , or more preferably 38.5 wt. % to 39.5 wt. %  $\text{Al}_2\text{O}_3$ ; 5 wt. % to 45 wt. % silicon dioxide ( $\text{SiO}_2$ ), preferably 7 wt. % to 8 wt. %  $\text{SiO}_2$ ; 4 wt. % to 30 wt. % magnesium oxide ( $\text{MgO}$ ), preferably 7 wt. % to 8 wt. %  $\text{MgO}$ ; and  
5 0.1 wt. % to 7 wt. % of iron (III) oxide ( $\text{Fe}_2\text{O}_3$ ), preferably 1 wt. % to 7 wt. %  $\text{Fe}_2\text{O}_3$ , or more preferably 2 wt. % to 3 wt. %  $\text{Fe}_2\text{O}_3$ . In another aspect, the steel ladle furnace slag can include, based on the total weight of the steel ladle furnace slag: 45 wt. % to 50 wt. % CaO, preferably 47 wt. % to 48 wt. % CaO; 5 wt. % to 10 wt. %  $\text{Al}_2\text{O}_3$ , preferably 8 wt. % to 9 wt. %  $\text{Al}_2\text{O}_3$ ; 27 wt. % to 35 wt. %  $\text{SiO}_2$ , preferably 30.5 wt. % to 31.5 wt. %  $\text{SiO}_2$ ; 5 wt. % to 10 wt. %  $\text{MgO}$ ,  
10 preferably 7 wt. % to 8 wt. %  $\text{MgO}$ ; and 1 wt. % to 5 wt. % of  $\text{Fe}_2\text{O}_3$ , preferably 3 wt. % to 4 wt. %  $\text{Fe}_2\text{O}_3$ . In some embodiments, the steel ladle furnace slag does not include electric arc furnace (EAF) steel slag and/or blast oxygen furnace (BOF) steel slag.

**[0008]** Catalyst compositions of the present invention that include the steel ladle furnace slag can be capable of catalyzing a chemical reaction (*e.g.*, a steam reforming reaction, a carbon  
15 dioxide reforming reaction, a denitrification reaction, a desulfurization reaction, a partial oxidation of hydrocarbons reaction, and the like). The particulate material can include a support material, a bulk metal catalyst, or both. Non-limiting examples of support material include a metal oxide (*e.g.*,  $\text{Al}_2\text{O}_3$ ,  $\text{SiO}_2$ , or both), a zeolite or a combination of both. The support material can also include a catalytic metal or a mixture of catalytic metals, the bulk  
20 metal catalyst, or combinations thereof. In a preferred instance, the support material can include a catalytic transition metal, post transition metal or any combination thereof.

**[0009]** In yet another aspect of the present invention, methods of binding a particulate material together are disclosed. A method can include (a) mixing the particulate material with a binder material comprising steel ladle furnace slag to form a mixture, (b) extruding the  
25 mixture and optionally drying the extruded mixture or pelletizing the mixture and optionally drying the formed pellets; and (c) optionally calcining the extruded mixture or the formed pellets. The mixture can be in particulate form. The shape and size of the pellets can vary in shape (*e.g.*, sphere, ring, rod, etc.) and size (*e.g.*, 1 to 100 mm). The catalytic particulate material prior to extruding can have nanometer to micrometer particles.

**[0010]** In still another aspect of the present invention, methods of catalyzing chemical reactions are described. A method can include contacting the composition of the present invention under conditions sufficient to catalyze the chemical reaction and produce a product(s). In some embodiments, the chemical reaction can be hydrocarbon reformation, preferably steam methane ( $\text{CH}_4$ ) reformation. In such a reaction, the reactants can include  $\text{H}_2\text{O}$

and a hydrocarbon(s), preferably CH<sub>4</sub>, and the products can include hydrogen (H<sub>2</sub>) and carbon monoxide (CO).

[0011] Other embodiments of the invention are discussed throughout this application. Any embodiment discussed with respect to one aspect of the invention applies to other aspects of the invention as well and vice versa. Each embodiment described herein is understood to be embodiments of the invention that are applicable to other aspects of the invention. It is contemplated that any embodiment discussed herein can be implemented with respect to any method or composition of the invention, and vice versa. Furthermore, compositions of the invention can be used to achieve methods of the invention.

[0012] The following includes definitions of various terms and phrases used throughout this specification.

[0013] “Slag” refers to a by-product produced during the steelmaking process. FIG. 1 illustrates a steel making process. BOF slag is slag produced from a BOF steel production process. EAF slag is slag produced from an EAF steel production process. Steel produced in a BOF or an EAF production process can be further processed into refined steel by using a ladle refining unit. “Steel ladle furnace” slag is slag produced from the ladle refining unit. As illustrated, slag is named based on the furnaces they are generated from.

[0014] The terms “about” or “approximately” are defined as being close to as understood by one of ordinary skill in the art. In one non-limiting embodiment, the terms are defined to be within 10%, preferably within 5%, more preferably within 1%, and most preferably within 0.5%.

[0015] The terms “wt.%”, “vol.%”, or “mol.%” refers to a weight percentage of a component, a volume percentage of a component, or molar percentage of a component, respectively, based on the total weight, the total volume of material, or total moles, that includes the component. In a non-limiting example, 10 grams of component in 100 grams of the material is 10 wt.% of component.

[0016] The term “bulk metal catalyst” as that term is used in the specification and/or claims, means that the catalyst includes one metal, and does not require a carrier or a support. The bulk metal catalyst can include two or more catalytic compounds bound together by the binder material of the present invention.

[0017] The term “substantially” and its variations are defined to include ranges within 10%, within 5%, within 1%, or within 0.5%.

[0018] The terms “inhibiting” or “reducing” or “preventing” or “avoiding” or any variation of these terms, when used in the claims and/or the specification includes any measurable decrease or complete inhibition to achieve a desired result.

[0019] The term “effective,” as that term is used in the specification and/or claims, means adequate to accomplish a desired, expected, or intended result.

[0020] The use of the words “a” or “an” when used in conjunction with any of the terms “comprising,” “including,” “containing,” or “having” in the claims, or the specification, may mean “one,” but it is also consistent with the meaning of “one or more,” “at least one,” and “one or more than one.”

[0021] The words “comprising” (and any form of comprising, such as “comprise” and “comprises”), “having” (and any form of having, such as “have” and “has”), “including” (and any form of including, such as “includes” and “include”) or “containing” (and any form of containing, such as “contains” and “contain”) are inclusive or open-ended and do not exclude additional, unrecited elements or method steps.

[0022] The compositions of the present invention can “comprise,” “consist essentially of,” or “consist of” particular ingredients, components, compositions, *etc.* disclosed throughout the specification. With respect to the transitional phrase “consisting essentially of,” in one non-limiting aspect, a basic and novel characteristic of the compositions of the present invention is that the steel ladle furnace slag is used as a binder material to bind particulate matter together to create a composition. The use of steel ladle furnace slag is believed to enhance the mechanical integrity of the resulting composition as compared to compositions that include other types of slag (*e.g.*, electric arc furnace steel slag and/or blast oxygen furnace steel slag).

[0023] Other objects, features and advantages of the present invention will become apparent from the following figures, detailed description, and examples. It should be understood, however, that the figures, detailed description, and examples, while indicating specific embodiments of the invention, are given by way of illustration only and are not meant to be limiting. Additionally, it is contemplated that changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description. In further embodiments, features from specific embodiments may be combined with features from other embodiments. For example, features from one embodiment may be combined with features from any of the other embodiments. In further embodiments, additional features may be added to the specific embodiments described herein.

### **BRIEF DESCRIPTION OF THE DRAWINGS**

[0024] Advantages of the present invention may become apparent to those skilled in the art with the benefit of the following detailed description and upon reference to the accompanying drawings.

5 [0025] FIG. 1 is an illustration of a steel making process.

[0026] FIG. 2 depicts a system to perform a chemical reaction using a catalyst composition of the present invention that includes steel ladle furnace slag as a binder material.

[0027] FIG. 3 depicts horizontal and vertical crush strength values for alumina-SFP compositions of the present invention.

10 [0028] FIG. 4 depicts methane ( $\text{CH}_4$ ) conversion of nickel/steel ladle furnace slag-alumina catalyst of the present invention for steam reforming of methane reaction.

[0029] FIG. 5 depicts  $\text{CH}_4$  conversion of reference nickel catalyst for steam reforming of methane reaction.

15 [0030] FIG. 6 depicts carbon monoxide ( $\text{CO}$ ) selectivity of nickel/steel ladle furnace slag-alumina catalyst of the present invention for steam reforming of methane reaction.

[0031] FIG. 7 depicts  $\text{CO}$  selectivity of reference nickel catalyst for steam reforming of methane reaction.

20 [0032] While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings. The drawings may not be to scale.

### **DETAILED DESCRIPTION OF THE INVENTION**

[0033] A discovery has been made that provide a solution to at least some of the problems associated with bound particulate material. The discovery is premised on the idea of using steel ladle furnace slag as an ingredient in binder materials useful in catalyst applications. For example, the binder material can be used in compositions for binding and/or shaping catalyst compositions.

[0034] These and other non-limiting aspects of the present invention are discussed in further detail in the following sections.

#### **A. Materials**

30 [0035] The compositions of the present invention can include binder material and particulate material. The binder material can adhere the particulate material together to form larger particulates and/or allow the particulate material to be shaped.

## 1. Binder Material

[0036] The binder material of the present invention can comprise, consist essentially of, or consist of steel ladle furnace slag. Steel ladle furnace slag is the byproduct from further refining of molten steel after coming out of a blast oxygen furnace or an electric arc furnace. The ladle furnace slag is produced in the final stages of steelmaking, when the steel is desulfurized in the transport ladle, during what is generally known as the secondary metallurgy process. The most important functions of the secondary refining processes are the final desulfurization, the degassing of oxygen, nitrogen, and hydrogen, the removal of impurities, and the final decarburization (done for ultralow carbon steels). This process can include processes to product long products (*e.g.*, wires, billets, blooms, rebars, sections, sheet piles, wire rods and the like) or flat products (*e.g.*, slabs, hot-rolled coils, cold-rolled coils, coated steel products, tinplates, and heavy plates). This processing produces steel ladle slag with lower iron content than blast oxygen furnace slag and/or electric arc furnace slag. In the context of the present invention, steel ladle slag can be used as a binder material to bind particulate matter together to create a composition. This steel ladle slag is believed to enhance the composition's integrity and performance. Thus, steel ladle slag can be used to fully or partially replace common adhesive/binder materials for catalyst shaping and can improve mechanical and/or thermal integrity of the resulting catalytic composition. Furthermore, the steel ladle furnace slag binder material can be used with or without any pre or post treatment, is inexpensive, is simple to manufacture on a commercial size (*e.g.*, it is a by-product produced during the steel refining process), and/or provides sustainability of natural resources that are used in producing binder materials.

[0037] In some embodiments, the composition of the present invention can include 1 wt.% to 60 wt.% of steel ladle furnace slag or at least one of, equal to one of, or between any two of 1, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, or 60 wt.% of the steel ladle furnace slag based on the total weight of the composition. In some embodiments, the composition includes at least 2 wt.%, or at least 5 wt.% of the steel ladle furnace slag based on total weight of the composition. In other embodiments, the composition can include 1 to 60 wt.%, 2 to 55 wt.%, or 5 to 25 wt.% of the steel ladle furnace slag based on total weight of the composition. In particular aspects, the steel ladle slag is not reacted with 1) a polymer to produce the binder material, and/or 2) an alkali metal oxide sol gel, or silica containing materials under hydrothermal conditions to produce the binder material.

[0038] Steel ladle slag can include oxides of calcium, silicon, aluminum, magnesium, iron, manganese, chromium, phosphorous, titanium, potassium, and sodium. The silicon and/or

aluminum oxides can also be in silicate and aluminate forms. Non-limiting examples of silicate and aluminate forms include mayenite or also known as  $A_{12}A_7$  ( $12CaO \cdot 7Al_2O_3$ ,  $Ca_{12}Al_{14}O_{33}$ ), gehlenite ( $2CaO \cdot Al_2O_3 \cdot SiO_2$ ,  $Ca_2Al_2SiO_7$ ), larnite ( $\beta$ - $2CaO \cdot SiO_2$ ,  $\beta$ - $Ca_2SiO_4$ ), shannonite also known as C3A ( $\gamma$ - $2CaO \cdot SiO_2$ ,  $\gamma$ - $Ca_2SiO_4$ ), and tricalcium aluminate ( $3CaO \cdot Al_2O_3$ ,  $Ca_3Al_2O_6$ ).

5 In some embodiments, steel ladle slag can include at least 20 wt.% up to 65 wt.% of CaO, or at least one of, equal to one of, or between any two of 20, 25, 30, 35, 40, 45, 50, 55, 60, or 65 wt.%, based on the total weight of the steel ladle furnace slag. The amount of alumina can be at least 5 wt.% up to 60 wt.%, or at least one of, equal to one of, or between any two of 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, and 60 wt.%, based on the total weight of the steel ladle  
10 furnace slag. MgO can be present, based on the total weight of the steel ladle furnace slag, from 4 wt.% up to 30 wt.%, or at least one of, equal to one of, or between any two of 4, 6, 10, 15, 20, 25, and 30 wt.%. Iron oxide, preferably  $Fe_2O_3$  can be present in at least 0.1 wt.% up to 7 wt.% or at least one of, equal to one of, or between any two of 0.1, 0.5, 1, 2, 3, 4, 5, 6, 7 wt.%, based on the total weight of the steel ladle furnace slag. Other oxides or materials can be  
15 present in less than 0.5 wt.%, or less than one of, equal to one of, or between any two of 0.5, 0.1, 0.05, 0.01, and 0 wt.%, based on the total weight of the steel ladle furnace slag. In some embodiments, the steel ladle furnace slag, based on the total weight of the steel ladle furnace slag, can include 20 wt. % to 65 wt. % CaO, 5 wt. % to 60 wt. %  $Al_2O_3$ , 5 wt. % to 45 wt. %  $SiO_2$ , 4 wt. % to 30 wt. % MgO, and 0.1 wt. % to 7 wt. % of  $Fe_2O_3$ . In another instance, the  
20 steel ladle furnace slag, based on the total weight of the steel ladle furnace slag, can include 20 wt. % to 45 wt. % CaO, 35 wt. % to 60 wt. %  $Al_2O_3$ , 5 wt. % to 45 wt. %  $SiO_2$ , 4 wt. % to 30 wt. % MgO, and 1 wt. % to 7 wt. % of  $Fe_2O_3$ . In certain embodiments, the steel ladle furnace slag, based on the total weight of the steel ladle furnace slag, can include 45 wt. % to 50 wt. % CaO, 5 wt. % to 10 wt. %  $Al_2O_3$ , 27 wt. % to 35 wt. %  $SiO_2$ , 5 wt. % to 10 wt. % MgO, and 1  
25 wt. % to 5 wt. %  $Fe_2O_3$ . In yet another embodiments, the steel ladle furnace slag, based on the total weight of the steel ladle furnace slag, can include 47 wt. % to 48 wt. % CaO, 8 wt. % to 9 wt. %  $Al_2O_3$ , 30.5 wt. % to 31.5 wt. %  $SiO_2$ , 7 wt. % to 8 wt. % MgO,; and 3 wt. % to 4 wt. % of  $Fe_2O_3$ .

## 2. Particulate Material

30 [0039] The particulate material that can be bound together by the steel ladle furnace slag binder material of the present invention can include a bulk metal catalyst, a support material, or any other component (e.g., urea particles, sulfates, phosphates and the like).

### a. Bulk metal catalyst

**[0040]** Bulk metal catalyst can include mixed metal oxides or mixed metal where the metals have catalytic activity and a total of the catalytic metals is greater than 80 wt.% up to 100 wt.%, based on the total weight of the catalyst. Bulk metal catalysts can include metals from Columns 1-15 of the Periodic Table. Non-limiting examples of metals used in bulk metal catalysts include niobium (Nb), vanadium, molybdenum (Mo), tungsten (W), iron (Fe), ruthenium (Ru), cobalt (Co), rhodium (Rh), nickel (Ni), palladium (Pd), platinum (Pt), copper (Cu), gold (Au), silver (Ag), zinc (Zn), gallium (Ga), the lanthanides such as lanthanum (La), cerium (Ce) and the like. By way of example, a desulfurization catalyst can include Mo, Co, and Nb. In another example, deoxygenation catalysts can include the metal combinations of nickel-tungsten oxides, cobalt-tungsten oxides, nickel-molybdenum oxides, cobalt-molybdenum oxides, nickel-molybdenum-tungsten oxides, cobalt-molybdenum-tungsten oxides, cobalt-nickel-tungsten oxides, cobalt-nickel-molybdenum oxides, cobalt-nickel-tungsten-molybdenum oxides, nickel-tungsten-niobium oxides, nickel-tungsten-vanadium oxides, cobalt-tungsten-vanadium oxides, cobalt-tungsten-niobium oxides, nickel-molybdenum-niobium oxides, nickel-molybdenum-vanadium oxides, nickel-molybdenum-tungsten-niobium oxides, nickel-molybdenum-tungsten-vanadium oxides, and the like, and combinations thereof. Reforming bulk metal catalysts can include nickel-cobalt oxides, nickel manganese oxides, nickel-iron oxides, or nickel-copper oxides. Other reforming catalyst can include combinations of Column 2 metals (*e.g.*, calcium, barium, and magnesium) with Columns 3-10 metal (*e.g.*, Zr, Mo, Ru, Os, Rh, Ir, Ni, Pd, Pt, Ti, Nb, W, V, a lanthanide (*e.g.*, La or Ce), or a combinations thereof with nesosilicate in a olivine type structure. Denitrification catalysts can include combinations of Fe, Cu, Mo, Co and Mn metals. The bulk-metal catalysts can be prepared by processes known to those having ordinary skill in the art, for example the bulk metal catalyst can be prepared by any one of the methods comprising liquid-liquid blending, solid-solid blending, or liquid-solid blending (*i.e.*, any of precipitation, co-precipitation, impregnation, complexation, gelation, crystallization, microemulsion, sol-gel, solvothermal, hydrothermal, sonochemical, or combinations thereof).

*b. Support material*

**[0041]** Support material can include a metal oxide, silicon carbide, magnesium silicate, or a zeolite, or any combination thereof. Non-limiting examples of metal oxides include titanium oxide, aluminum oxide (*e.g.*,  $\gamma$ -,  $\theta$ - or  $\Delta$ -aluminum oxide or any combination thereof, cerium oxide, silicon oxide, zinc oxide, magnesium oxide, aluminum-silicon oxide, and or any combination thereof. In a preferred embodiments, aluminum oxide and/or silicon oxide are used.

**[0042]** Zeolites have a porous structure that can accommodate a wide variety of cations, such as protonic ( $H^+$ ), ammonium cations ( $NH^+$ ), sodium cations ( $Na^+$ ), potassium cations ( $K^+$ ), calcium cations ( $Ca^{2+}$ ), magnesium cations ( $Mg^{2+}$ ), and others. These positive ions can be exchanged for the transition metal in a contact solution. The zeolite material can be a naturally occurring zeolite, a synthetic zeolite, a zeolite that has other materials in the zeolite framework, or combinations thereof. X-ray diffraction (XRD) analysis and scanning electron microscopy (SEM) may be carried out to determine the properties of zeolite materials, including their crystallinity, size and morphology. The network of such zeolites is made up of  $SiO_4$  and  $AlO_4$  tetrahedra which are joined *via* shared oxygen bridges. An overview of the known structures may be found, for example, in Meier *et al.*, “Atlas of Zeolite Structure Types”, *Elsevier*, 5th edition, Amsterdam 2001. The ion exchange capacity of the zeolite can range from 0.1 to 300 %, 10% to 300%, 20% to 200%, or 0.1%, 10%, 20%, 50%, 100%, 150%, 200%, 250%, 300%, or any range or value there between. X and Y Zeolites that have a pore size large enough for benzene to diffuse into the zeolite and phenol to diffuse out the zeolite can be used. Non-limiting examples of zeolites include, MFI, \*BEA, BEC, FAU, MOR, or USY structures and mixed structures of two or more of the abovementioned structures. In some embodiments, the zeolite includes phosphorous. Zeolites can be in a pure silica ( $Si/Al = \infty$ ) form or with a small amount of Al, for example, a MFI, \*BEA, MOR, or a FAU framework structure. Non-limiting examples of zeolites include ABW, ACO, AEI, AEL, AEN, AET, AFG, AFI, AFN, AFO, AFR, AFS, AFT, AFX, AFY, AHT, ANA, APC, APD, AST, ASV, ATN, ATO, ATS, ATT, ATV, AWO, AWW, BCT, \*BEA, BEC, BIK, BOG, BPH, BRE, CAN, CAS, CDO, CFL, CGF, CGS, CHA, CHI, CLO, CON, \*CTH, CZP, DAC, DDR, DFO, DFT, DOH, DON, EAB, EDI, EMT, EON, EPI, ERI, ESV, ETR, EUO, EZT, FAR, FAU, FER, FRA, \*FWT, GIS, GIU, GME, GON, GOO, HEU, IFR, IHW, ISV, ITE, ITH, ITW, IWR, IWV, IWW, JBW, KFI, LAU, LEV, LIO, LIT, LOS, LOV, LTA, LTL, LTN, MAR, MAZ, MEI, MEL, MEP, MER, MFI, MFS, MON, MOR, MOZ, \*MRE, MSE, MSO, MTF, MTN, MTT, MTW, MWW, NAB, NAT, NES, NON, NPO, NSI, OBW, OFF, OSI, OSO, OWE, PAR, PAU, PHI, PON, RHO, RON, RRO, RSN, RTE, RTH, RUT, RWR, RWY, SAO, SAS, SAT, SAV, SBE, SBS, SBT, SFE, SFF, SFG, SFH, SFN, SFO, SGT, SIV, SOD, SOS, SSY, STF, STI, STT, SZR, TER, THO, TON, TSC, TUN, UEI, UFI, UOZ, USI, UTL, VET, VFI, VNI, VSV, WEI, WEN, YUG and ZON. The above nomenclature of three-letter codes corresponds to the “IUPAC Commission of Zeolite Nomenclature”. The zeolite support can be a H-ZSM-5 zeolite.

**[0043]** Zeolite material can also include mesoporous zeolite materials of the family which are combined under the name “MCM” in the literature, wherein this name is not a particular

structure type (cf. <http://www.iza-structure.org/databases>). Non-limiting examples of MCM zeolites include MCM-1, MCM-2, MCM-3, MCM-4, MCM-5, MCM-9, MCM-10, MCM-14, MCM-22, MCM-35, MCM-37, MCM-41, MCM-48, MCM-49, MCM-58, MCM-61, MCM-65 or MCM-68 in the literature.

5 **[0044]** In some embodiments, the zeolite material can be a silicate, an aluminum silicate, an aluminum phosphate, a silicon aluminum phosphate, a metal aluminum phosphate, a metal aluminum phosphosilicate, a gallium aluminum silicate, a gallium silicate, a boroaluminum silicate, a boron silicate or a titanium silicate, or any combination thereof. Aluminum silicate include a crystalline substance with spatial network structure of the general formula  
 10  $M_n^+[(AlO_2)_x(SiO_2)_y]_xH_2O$ , which is composed of  $SiO_4/2$  and  $AlO_4/2$  tetrahedra which are linked by common oxygen atoms to form a regular three-dimensional network. The atomic ratio of  $Si/Al=y/x$  is always greater than/equal to 1 according to the so-called “Löwenstein's rule” which prohibits two neighboring negatively charged  $AlO_4/2$  tetrahedra from occurring next to each other. Although more exchange sites are available for metals at a low  $Si/Al$  atomic  
 15 ratio, the zeolite increasingly becomes more thermally unstable.

**[0045]** The above-named zeolite materials can be used in the method both in the alkaline form, for example in the Na and/or K form, and in the alkaline earth form, ammonium form or in the H form. In addition, it is also possible to use the zeolite material in a mixed form. Zeolites may be obtained from a commercial manufacturer such as Zeolyst (Valley Forge,  
 20 Pennsylvania, U.S.A.). Which zeolite material is to be used in the method can depends on the purpose of use of the catalyst to be produced. A large number of methods are known in the state of the art to tailor the properties of zeolite materials, for example the structure type, the pore diameter, the channel diameter, the chemical composition, the ion exchangeability as well as activation properties, to a corresponding purpose of use.

25 **[0046]** The support material can include one or more catalytic metals. Catalytic metals include metals in reduced form, metal oxides, or mixtures thereof (“collectively catalytic metals”). The catalytic metal can be chosen depending on the type of reaction to be performed. By way of example, steam reforming of hydrocarbons can include Ni as a catalytic metal. Catalytic metals include Column 1 or 2 metals, transition metals, post-transition metals, and  
 30 lanthanides (atomic number 57-71) of the Periodic Table. Non-limiting examples of transition metals and post-transition metals include Cr, Mo, W, V, Nb, Mn, Fe, Ru, Co, Rh, Ni, Pd, Cu, Ag, Zn, Cd, Bi, Ga, In, Sn, Te, and Sb or any combination thereof. Non-limiting examples of Columns 1 and 2 metals include Na, Mg, Ca, K, Cs or any combination thereof. Non-limiting examples of lanthanides include La, Ce, or any combination thereof. The support material of

the present invention can include up to 20 wt. % of the catalytic metal, from 0.1 wt.% to 20 wt. %, from 1 wt. % to 10 wt. %, or from 3 wt. % to 7 wt. % and all wt.% there between or at least to one of, equal to one or, or between any two of 0.1, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.6, 7, 7.5, 8, 8.5, 9, 9.5, 10, 10.5, 11, 11.5, 12, 12.5, 13, 13.5, 14, 14.5, 15, 15.5, 16, 16.5, 17, 17.5, 18, 18.5, 19, 19.5, and 20 wt.%. Catalyst for desulfurization, deoxygenation, denitrification, reforming can include the same metals as bulk-metal catalyst except in smaller quantities.

[0047] The metals used to prepare the support material of the present invention can be provided in varying oxidation states as metallic, oxide, hydrate, or salt forms typically depending on the propensity of each metals stability and/or physical/chemical properties. The metals in the catalyst can also exist in one or more oxidation states. Metals or metal oxides used in the preparation of the catalytic metal containing support material can be provided in stable oxidation states as complexes with monodentate, bidentate, tridentate, or tetradentate coordinating ligands such as for example iodide, bromide, sulfide, thiocyanate, chloride, nitrate, azide, fluoride, hydroxide, oxalate, water, isothiocyanate, acetonitrile, pyridine, ammonia, ethylenediamine, 2,2'-bipyridine, 1,10-phenanthroline, nitrite, triphenylphosphine, cyanide, carbon monoxide, or mixtures thereof. In some embodiments, the metals are impregnated into the support material as aqueous solutions of metal nitrate, metal nitrate hydrates, metal nitrate trihydrates, metal nitrate hexahydrates, and metal nitrate nonahydrates. A non-limiting example of a commercial source of the above mentioned catalytic metals is Sigma Aldrich® (U.S.A).

*c. Other Materials*

[0048] Other materials can include particulates that can be beneficial when bound together. For example, particulates suitable for fertigation can be used in the context of the present invention. Fertilizer compositions can include compounds or nutrients that can include sources of nitrogen, phosphorous, potassium and sulfur (e.g., urea, lysine, ammonium phosphite, ammonium nitrate, ammonium sulfate, diammonium phosphate (DAP), monoammonium phosphate (MAP), urea-formaldehyde, ammonium chloride, and potassium nitrate and the like).

**B. Composition Preparation**

[0049] As illustrated in the Examples section, the composition of the present invention can be produced using blending and shaping methodology known in the art. In some embodiments, the compositions can be made using extruding methodology. The method of binding the particulate material described throughout the specification together can include mixing the

binder with particulate material, extruding the mixture, and pelletizing the extrudates. After each mixing, extruding and pelletizing step, the materials can optionally be dried, calcined, or both. The binder material and particulate material can be mixed using high speed mixer, ball milling, or the like at 25 °C to 35 °C until the components are well mixed. The duration of mixing can be established by one of skill in the art (*e.g.*, 0.25 hours to 24 hours). The particulate material and the binder material can be mixed in various amounts necessary for the application of use. By way of example, 1 to 60 wt.% of steel ladle furnace slag can be mixed with 40 wt.% to 99 wt.% of particulate matter. The amount of steel ladle furnace slag can be at least one of, equal to one of, or between any two of 1, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, and 60 wt.%, based on the total weight of the composition. After mixing, the particulate/binder mixture can optionally be dried at 200 to 300 °C, or at least one of, equal to one of, or between any two of 200, 210, 220, 230, 240, 250, 260, 270, 280, 290, and 300 °C until the moisture content is constant, for example 0.25 hours to 5 hours, or any range there between. Temperatures can be ramped at a rate of 2 to 10 °C per minute to obtain the drying temperature.

**[0050]** The particulate/binder mixture (or the dried mixture) can be shaped using known shaping methodology. In one embodiment, the particulate/binder mixture (or the dried mixture) can be extruded using known extrusion equipment. Extruding can be performed at a temperature from 0 °C to 700 °C and a screw speed from 1 to 200 rpm. Single or multi-feed extruders can be used. In another embodiment, the particulate/binder mixture (or the dried mixture) can be pelletized at a force of 5 to 10 Tons or about 8 Tons using a die of a desired size (*e.g.*, 1 mm to 20 mm, or 2 to 15 mm, or any range or value there between) for a desired amount of time (*e.g.*, 0.25 hours to 1 hour, or 0.5 hour to 0.75 hour or any range or value there between). After mixing, the extrudates or pellets can optionally be dried or calcine or both. Drying conditions can include a temperature of at 200 to 300 °C, or at least one of, equal to one of, or between any two of 200, 210, 220, 230, 240, 250, 260, 270, 280, 290, and 300 °C until the moisture content is constant, for example 0.25 hours to 5 hours, or any range there between at atmospheric pressure. Temperatures can be ramped at a rate of 2 to 10 °C per minute to obtain the drying temperature. Calcination conditions can include a temperature of at 500 to 900 °C, or at least one of, equal to one of, or between any two of 500, 550, 600, 650, 700, 750, 800, 850, and 900 °C for a desired amount of time, for example 0.25 hours to 5 hours, or any range there between, at atmospheric pressure. Temperatures can be ramped at a rate of 2 °C to 10 °C per minute to obtain the calcining temperature.

### **C. Compositions**

[0051] The composition produce by the method exemplified in the Examples and described in Section B, can include the binder material and the particulate material as described in the materials section A. The composition can include at least 1 wt.% preferably at least 5 wt.%, or 1 wt.% to 60 wt.% or 5 wt.% to 25 wt.% or any value or range there between of the steel ladle furnace slag. The shape of the composition can be of any form or size. Non-limiting examples of shapes include rods, rings, spherical, cylindrical, tablet, random shapes, or the like. The shapes can be obtained *via* palletization or extrusion or the like. Materials of various shapes can be used in combination. The composition can meet the physical and mechanical properties for the intended use. For example, the catalyst can be a catalyst having have a horizontal crush strength of at least one of, equal to one of, or between two of 250 daN, 300 daN, 350 daN, 400 daN, 450 daN and 500 daN, as measured by ASTM D4179-11.

#### **D. System for Production of Chemical Compounds**

[0052] The compositions of the present invention, when they include catalytic particulate material, can be used for a variety of chemical reactions. In one embodiment, the composition can include steel ladle furnace slag as a binder material and particulate catalytic material that is bound together with the binder material. In one non-limiting aspect, alumina and/or nickel metal can be used (e.g., in a steam reforming reaction).

[0053] FIG. 2 depicts a schematic for a system to produce a chemical compound. The system 100 can include an inlet 102 for a first reactant feed, an inlet 104 for a second reactant feed, a reaction zone 106 (*e.g.*, a continuous flow reactor selected from a fixed-bed reactor, a fluidized reactor, or a moving bed reactor) that is configured to be in fluid communication with the inlets 102 and 104, and an outlet 108 configured to be in fluid communication with the reaction zone 106 and configured to remove a product stream from the reaction zone. In some instances, a second reactant feed may not be needed and second inlet 104 may also not be needed. The reactant zone 106 can include a composition of the present invention. The first reactant feed can enter the reaction zone 106 *via* the inlet 102. After a sufficient amount of the first reactant and catalyst have been placed in the reaction zone 106, and if desired, a second reactant feed can enter the reaction zone through the feed inlet 104. In some embodiments, the first or second reactant feeds can be used to maintain a pressure in the reaction zone 106. In some embodiments, the reactant feed streams include inert gas (*e.g.*, nitrogen or argon). In some embodiments, the reactant feeds are provided at the same timer or in reverse order. In some embodiments, only one reactant feed is used. In other embodiments, three or more reactant feeds are used. After a sufficient amount of time, the product stream can be removed

from the reaction zone 106 *via* product outlet 108. The product stream can be sent to other processing units, stored, and/or transported.

[0054] System 100 can include one or more heating and/or cooling devices (*e.g.*, insulation, electrical heaters, jacketed heat exchangers in the wall) or controllers (*e.g.*, computers, flow valves, automated valves, *etc.*) that are necessary to control the reaction temperature and pressure of the reaction mixture. While only one reactor is shown, it should be understood that multiple reactors can be housed in one unit or a plurality of reactors housed in one heat transfer unit.

### **EXAMPLES**

[0055] The present invention will be described in greater detail by way of specific examples. The following examples are offered for illustrative purposes only, and are not intended to limit the invention in any manner. Those of skill in the art will readily recognize a variety of noncritical parameters which can be changed or modified to yield essentially the same results.

#### **Example 1**

##### **(Preparation of a Composition of the Present Invention and Comparative Examples)**

[0056] Aluminum oxide ( $\alpha$  phase) was obtained from a commercial source and was used to as a support material (particulate material). Portland cement, bentonite, and electric arc furnace (EAF) slag binder materials were obtained as comparative binder material. Steel ladle furnace slag binder material of the present invention was obtained from Hadeed iron and steel company (Saudi Arabia) flat steel (SFP) and long steel processes (SLP). The composition of the particulate and the binder material of the present invention are listed in Table 1.

**Table 1**

| Component                             | Binder A<br>(SFP) – F1 | Binder B<br>(SLP) | Bentonite <sup>1</sup> | Cement <sup>2</sup> |
|---------------------------------------|------------------------|-------------------|------------------------|---------------------|
| CaO (wt.%)                            | 43.59                  | 47.29             | 2                      | 65                  |
| Al <sub>2</sub> O <sub>3</sub> (wt.%) | 38.03                  | 8.81              | 21                     | 5                   |
| SiO <sub>2</sub> (wt.%)               | 7.23                   | 31.02             | 67                     | 21                  |
| MgO (wt.%)                            | 7.21                   | 7.52              | 3                      | 2                   |
| Fe <sub>2</sub> O <sub>3</sub> (wt.%) | 2.79                   | 3.33              | 4                      | 4                   |

1. Technical report TR-10-44; Clay Technology AB, 2010; 2. NIST 1880b.

[0057] Those materials are mixed in the amounts shown in Table 2 with the alpha-alumina matrix at a speed of 1500 rpm for 7 minutes. The binder/alumina mixtures was dried at 250 °C for 2 hours using a ramping rate of 2 °C / minute to remove any moisture. The dried mixture

was placed in a 13.0 mm die and a force of 8 Tons was applied for 30 minutes to pelletize the mixture. The pellets were calcined at 850 °C in a muffle furnace for 2 hours using a ramping rate of 2 °C / minute.

Table 2

| Sample ID# | Binder A (SFP) – F1 (grams) | Alumina Matrix (grams) | Bentonite (grams) | Cement (grams) | EAF | Kaolin |
|------------|-----------------------------|------------------------|-------------------|----------------|-----|--------|
| 01         | 0                           | 9                      | -                 | -              |     |        |
| 02         | 0.5                         | 8.5                    | -                 | -              |     |        |
| 03         | 1.0                         | 8.0                    | -                 | -              |     |        |
| 04         | 1.5                         | 7.5                    | -                 | -              |     |        |
| 05         | 2.0                         | 7.0                    | -                 | -              |     |        |
| 06         | 2.5                         | 6.5                    | -                 | -              |     |        |
| 07         | -                           | 8.5                    | 0.5               | -              |     |        |
| 08         | -                           | 8.5                    | -                 | 0.5            |     |        |
| 09         |                             | 8.5                    |                   |                | 0.5 |        |
| 10         |                             | 8.5                    |                   |                |     | 0.5    |

Example 2

## (Testing of Example 1 Samples)

[0058] These different formulations of Example 1 were tested for their mechanical performance, crushing strength test, vertically and horizontally. The prepared pellets (samples 01-07, and 09, Table 2) were tested using versatile crushing strength machine to confirm their mechanical integrity. Sample number 01 showed extremely low strength, once external load was applied. This output was anticipated as the pellet, that is purely alumina, had no binding agent. The addition of SFP-F1 binder of the present invention, from samples 02 to 06, was in the order of 5 wt.%, 10 wt.%, 15 wt.%, 20 wt.%, and 25 wt.%, respectively. FIG. 3 is a graphical representation of the crush strength. From the data, it was determined that the addition of the steel ladle furnace slag of the present invention dramatically enhanced the mechanical integrity of the pellet reaching 289 daN vertically. Samples 04, 05, and 06 were able to withstand up the maximum external load supplied by the machine, 450 daN, without an apparent crack initiation within the pellet.

[0059] The comparative samples that included bentonite, cement (Portland), EAF slag and kaolin. The prepared pellets using bentonite, cement, and kaolin were not able to hold themselves together after palletization with 5 wt.% of binder material. Similarly, the EAF type slag that was acquired was tested. The results as described in Table 3 below shows that the crushing strength of pellets composes of 5 wt.% of EAF slag was inferior to the crushing strength of the pellets made of 5 wt.% of steel ladle furnace slag of the present invention.

| Binder Agent                        | Crushing strength (daN) |
|-------------------------------------|-------------------------|
| None                                | 0                       |
| Bentonite                           | 0                       |
| Cementite                           | 0                       |
| Ladle slag of the present invention | 289                     |
| EAF slag                            | 2.75                    |

### Example 3

#### (Catalyst Preparation and Steam Reforming of Methane (SMR))

[0060] The SFP-alumina composition of the present invention (Example 1) was impregnated with nickel metal using known impregnation methodology. SFP (5 wt.%) and  $\alpha$ -Al<sub>2</sub>O<sub>3</sub> powder were mixed together, dried at 250 °C for 2 hrs, and pelletized for 30 minutes at 8 Tons pressure. The pellets were impregnated with approximately 5 wt.% Ni in the form of Ni nitrate dehydrates, followed by calcination at 850 °C for 2 hrs.

[0061] FIGS. 4-7 are methane conversion and CO selectivity for the catalyst of the present invention and the reference SMR catalyst. From the testing results indicated it was determined that the SMR reactivity of the Ni/SFP-alumina catalyst of the present invention was either comparable to the reference SMR catalyst or slightly less, under almost similar testing conditions. At SMR conditions of a GHSV of 35,000 h<sup>-1</sup>, 800 °C and 50 hours time on stream the of Ni/SFP-alumina catalyst had a similar performance to many commercial catalysts (See, Azo materials web site at <https://www.azom.com/article.aspx?ArticleID=12721>). The SMR reference catalyst had a better performance than the catalyst of the present invention. However, this was attributed to the SMR reference catalyst having double active site (Ni) concentration as compared to our catalyst and has additional promoters such as potassium unlike the catalyst prepared in this invention (See, FIGS. 4 and 5). CO selectivity for the Ni/SFP-alumina catalyst was slightly greater compared to the reference catalyst (70% vs. 60%, FIGS. 6 and 7, respectively). There was no deactivation in more than 50 hours on stream for the Ni/SFP-alumina catalyst of the present invention.

[0062] In the context of the present invention, at least 20 embodiments are now described. Embodiment 1 is a composition. The composition includes a binder material containing steel ladle furnace slag; and a particulate material bound together with the binder material. Embodiment 2 is the composition of embodiment 1, wherein the composition is a catalyst capable of catalyzing a chemical reaction. Embodiment 3 is the composition of embodiment 2, wherein the particulate material includes a support material, a bulk metal catalyst, or both. Embodiment 4 is the composition of embodiment 3, wherein the support material includes a metal oxide or a zeolite, preferably aluminum oxide (Al<sub>2</sub>O<sub>3</sub>) or silicon oxide (SiO<sub>2</sub>).

Embodiment 5 is the composition of any one of embodiments 3 to 4, wherein the support material includes a catalytic metal, a mixture of catalytic metals, mixed metal oxides, or combinations thereof, preferably a transition metal. Embodiment 6 is the composition of any one of embodiments 1 to 5, wherein the composition has a horizontal crush strength of 250 daN to 500 daN, as measured by ASTM D4179. Embodiment 7 is the composition of any one of embodiments 1 to 6, wherein the composition includes at least 1 wt. %, preferably at least 5 wt. %, of the steel ladle furnace slag. Embodiment 8 is the composition of embodiment 7, wherein the composition includes 1 wt. % to 60 wt. %, preferably 5 wt. % to 25 wt. %, of the steel ladle furnace slag. Embodiment 9 is the composition of any one of embodiments 1 to 8, wherein the steel ladle furnace slag includes, based on the total weight of the steel ladle furnace slag: 20 wt. % to 65 wt. % calcium oxide (CaO); 5 wt. % to 60 wt. % aluminum oxide (Al<sub>2</sub>O<sub>3</sub>); 5 wt. % to 45 wt. % silicon dioxide (SiO<sub>2</sub>); 4 wt. % to 30 wt. % magnesium oxide (MgO); and 0.1 wt. % to 7 wt. % of iron (III) oxide (Fe<sub>2</sub>O<sub>3</sub>). Embodiment 10 is the composition of embodiment 9, wherein the steel ladle furnace slag includes, based on the total weight of the steel ladle furnace slag: 20 wt. % to 45 wt. % CaO; 35 wt. % to 60 wt. % Al<sub>2</sub>O<sub>3</sub>; 5 wt. % to 45 wt. % SiO<sub>2</sub>; 4 wt. % to 30 wt. % MgO; and 1 wt. % to 7 wt. % of Fe<sub>2</sub>O<sub>3</sub>. Embodiment 11 is the composition of any one of embodiments 1 to 8, wherein the steel ladle furnace slag includes, based on the total weight of the steel ladle furnace slag: 45 wt. % to 50 wt. % CaO; 5 wt. % to 10 wt. % Al<sub>2</sub>O<sub>3</sub>; 27 wt. % to 35 wt. % SiO<sub>2</sub>; 5 wt. % to 10 wt. % MgO; and 1 wt. % to 5 wt. % Fe<sub>2</sub>O<sub>3</sub>. Embodiment 12 is the composition of embodiment 11, wherein the steel ladle furnace slag includes, based on the total weight of the steel ladle furnace slag: 47 wt. % to 48 wt. % CaO; 8 wt. % to 9 wt. % Al<sub>2</sub>O<sub>3</sub>; 30.5 wt. % to 31.5 wt. % SiO<sub>2</sub>; 7 wt. % to 8 wt. % MgO; and 3 wt. % to 4 wt. % of Fe<sub>2</sub>O<sub>3</sub>. Embodiment 13 is the composition of any one of embodiments 1 to 12, wherein the composition is in particulate form. Embodiment 14 is the composition of any one of embodiments 1 to 13, wherein the composition has a spherical shape, a ring shape, a cylindrical shape, or a tablet shape. Embodiment 15 is the composition of any one of embodiments 1 to 14, wherein the composition is extruded. Embodiment 16 is the composition of any one of embodiments 1 to 15, wherein the composition does not include either of electric arc furnace steel slag and blast oxygen furnace steel slag. Embodiment 17 is the composition of any one of embodiments 1 and 6 to 16, wherein the composition is a fertilizer granule and the particulate material is a fertilizer capable of fertilizing a soil or a plant.

**[0063]** Embodiment 18 is a method of binding a particulate material together, the method includes the steps of: (a) mixing the particulate material with a binder material containing steel ladle furnace slag to form a mixture; (b) extruding the mixture and optionally drying the

extruded mixture or pelletizing the mixture and optionally drying the formed pellets; and (c) optionally calcining the extruded mixture or the formed pellets. Embodiment 19 is a method of catalyzing a chemical reaction, the method further includes the step of contacting the composition of any one of embodiments 2 to 16 with a reactant(s) under conditions sufficient to catalyze the chemical reaction and produce a product(s). Embodiment 20 is the method of embodiment 19, wherein the chemical reaction is hydrocarbon reformation, preferably steam methane ( $\text{CH}_4$ ) reformation, the reactants include  $\text{H}_2\text{O}$  and a hydrocarbon(s), preferably  $\text{CH}_4$ , and the products include hydrogen ( $\text{H}_2$ ) and carbon monoxide ( $\text{CO}$ ).

**[0064]** Although embodiments of the present application and their advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the embodiments as defined by the appended claims. Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, composition of matter, means, methods and steps described in the specification. As one of ordinary skill in the art will readily appreciate from the above disclosure, processes, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein can be utilized. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps.

## CLAIMS

1. A composition comprising:  
a binder material comprising steel ladle furnace slag; and  
a particulate material bound together with the binder material.
2. The composition of claim 1, wherein the composition is a catalyst capable of catalyzing a chemical reaction.
3. The composition of claim 2, wherein the particulate material comprises a support material, a bulk metal catalyst, or both.
4. The composition of claim 3, wherein the support material comprises a metal oxide or a zeolite, preferably aluminum oxide ( $\text{Al}_2\text{O}_3$ ) or silicon oxide ( $\text{SiO}_2$ ).
5. The composition of any one of claims 3 to 4, wherein the support material comprises a catalytic metal, a mixture of catalytic metals, mixed metal oxides, or combinations thereof, preferably a transition metal.
6. The composition of any one of claims 1 to 4, wherein the composition has a horizontal crush strength of 250 daN to 500 daN, as measured by ASTM D4179.
7. The composition of any one of claims 1 to 4, wherein the composition comprises at least 1 wt. %, preferably at least 5 wt. %, of the steel ladle furnace slag.
8. The composition of claim 7, wherein the composition comprises 1 wt. % to 60 wt. %, preferably 5 wt. % to 25 wt. %, of the steel ladle furnace slag.
9. The composition of anyone of claims 1 to 4, wherein the steel ladle furnace slag comprises, based on the total weight of the steel ladle furnace slag:  
20 wt. % to 65 wt. % calcium oxide ( $\text{CaO}$ );  
5 wt. % to 60 wt. % aluminum oxide ( $\text{Al}_2\text{O}_3$ );  
5 wt. % to 45 wt. % silicon dioxide ( $\text{SiO}_2$ );  
4 wt. % to 30 wt. % magnesium oxide ( $\text{MgO}$ ); and  
0.1 wt. % to 7 wt. % of iron (III) oxide ( $\text{Fe}_2\text{O}_3$ ).
10. The composition of claim 9, wherein the steel ladle furnace slag comprises, based on the total weight of the steel ladle furnace slag:  
20 wt. % to 45 wt. %  $\text{CaO}$ ;  
35 wt. % to 60 wt. %  $\text{Al}_2\text{O}_3$ ;  
5 wt. % to 45 wt. %  $\text{SiO}_2$ ;

- 4 wt. % to 30 wt. % MgO; and  
1 wt. % to 7 wt. % of Fe<sub>2</sub>O<sub>3</sub>.
11. The composition of anyone of claims 1 to 4, wherein the steel ladle furnace slag comprises, based on the total weight of the steel ladle furnace slag:  
45 wt. % to 50 wt. % CaO;  
5 wt. % to 10 wt. % Al<sub>2</sub>O<sub>3</sub>;  
27 wt. % to 35 wt. % SiO<sub>2</sub>;  
5 wt. % to 10 wt. % MgO; and  
1 wt. % to 5 wt. % Fe<sub>2</sub>O<sub>3</sub>.
12. The composition of claim 11, wherein the steel ladle furnace slag comprises, based on the total weight of the steel ladle furnace slag:  
47 wt. % to 48 wt. % CaO;  
8 wt. % to 9 wt. % Al<sub>2</sub>O<sub>3</sub>;  
30.5 wt. % to 31.5 wt. % SiO<sub>2</sub>;  
7 wt. % to 8 wt. % MgO; and  
3 wt. % to 4 wt. % of Fe<sub>2</sub>O<sub>3</sub>.
13. The composition of any one of claims 1 to 4, wherein the composition is in particulate form.
14. The composition of any one of claims 1 to 4, wherein the composition has a spherical shape, a ring shape, a cylindrical shape, or a tablet shape.
15. The composition of any one of claims 1 to 4, wherein the composition is extruded.
16. The composition of any one of claims 1 to 4, wherein the composition does not include either of electric arc furnace steel slag and blast oxygen furnace steel slag.
17. The composition of claim 1, wherein the composition is a fertilizer granule and the particulate material is a fertilizer capable of fertilizing a soil or a plant.
18. A method of binding a particulate material together, the method comprising:  
(a) mixing the particulate material with a binder material comprising steel ladle furnace slag to form a mixture;  
(b) extruding the mixture and optionally drying the extruded mixture or pelletizing the mixture and optionally drying the formed pellets; and  
(c) optionally calcining the extruded mixture or the formed pellets.

19. A method of catalyzing a chemical reaction, the method comprising contacting the composition of any one of claims 2 to 3 with a reactant(s) under conditions sufficient to catalyze the chemical reaction and produce a product(s).
20. The method of claim 19, wherein the chemical reaction is hydrocarbon reformation, preferably steam methane ( $\text{CH}_4$ ) reformation, the reactants comprise  $\text{H}_2\text{O}$  and a hydrocarbon(s), preferably  $\text{CH}_4$ , and the products comprise hydrogen ( $\text{H}_2$ ) and carbon monoxide ( $\text{CO}$ ).

1/5

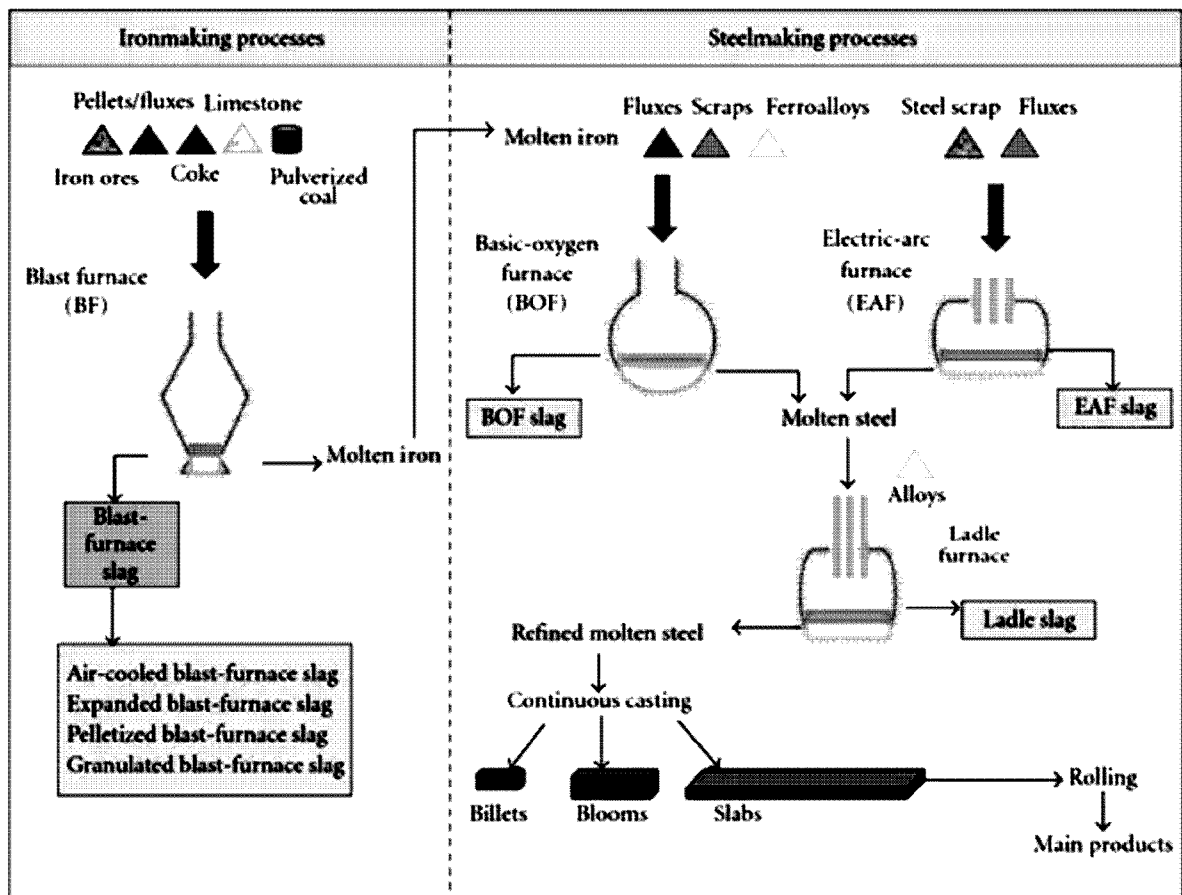


FIG. 1

2/5

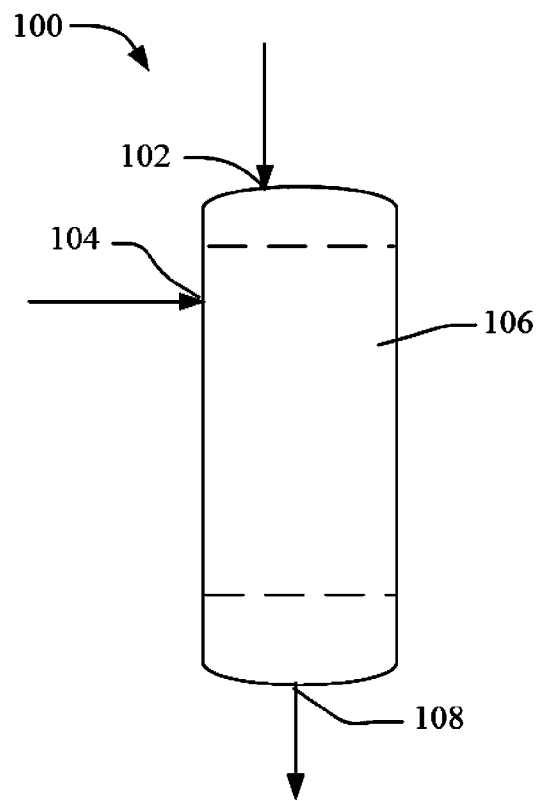
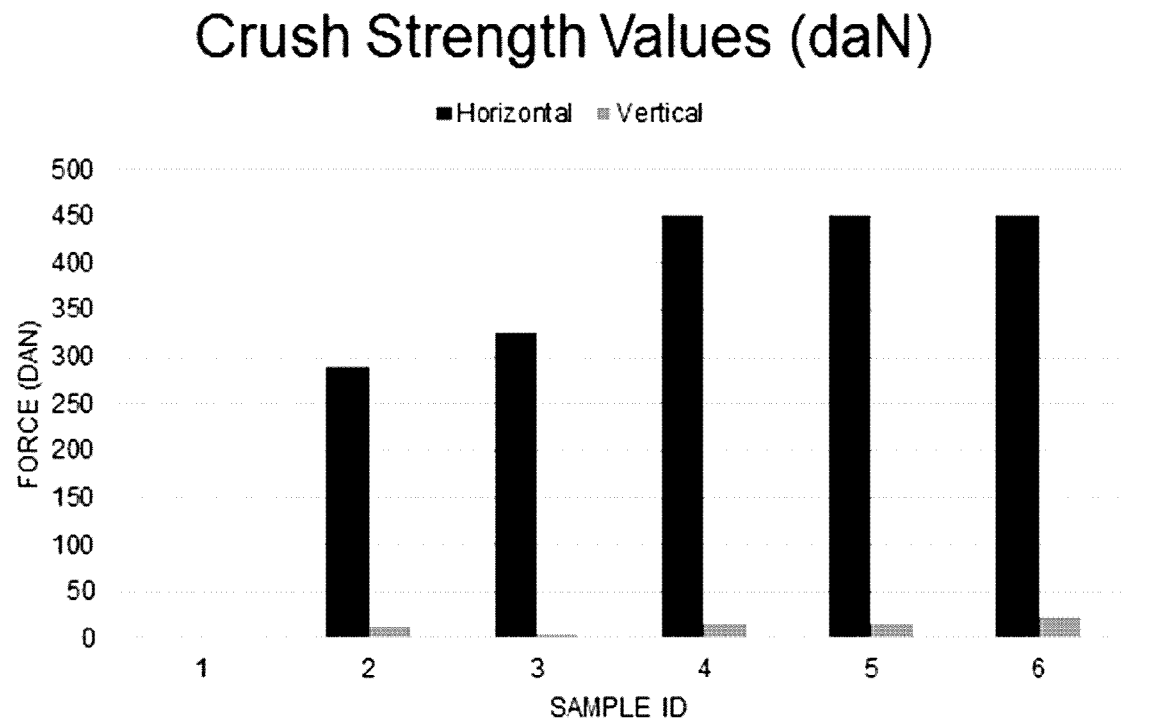


FIG. 2

3/5

**FIG. 3**

4/5

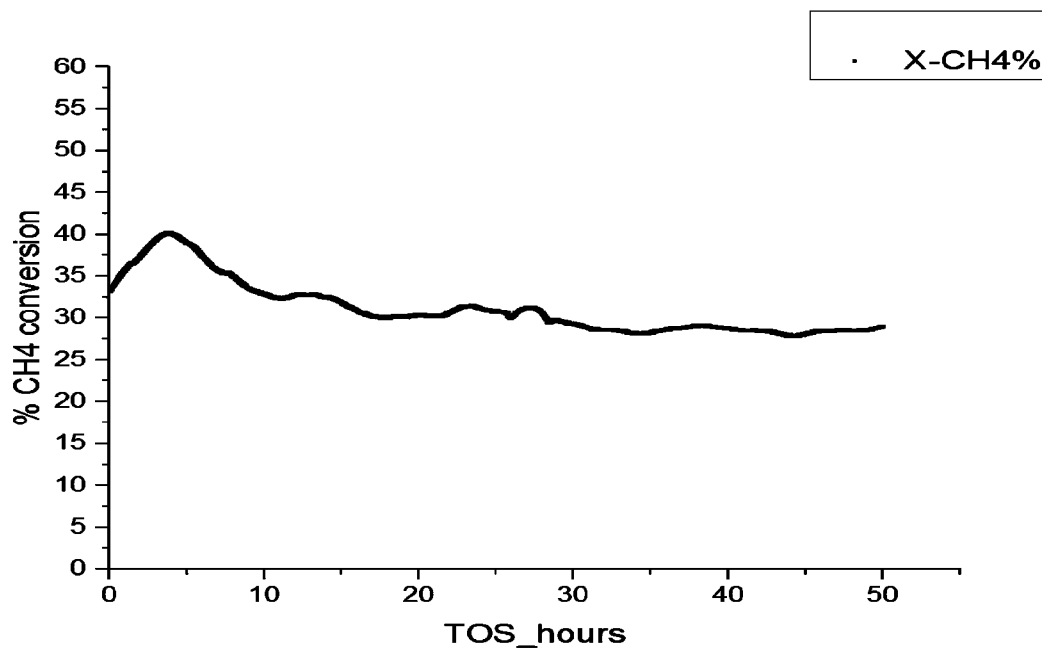


FIG. 4

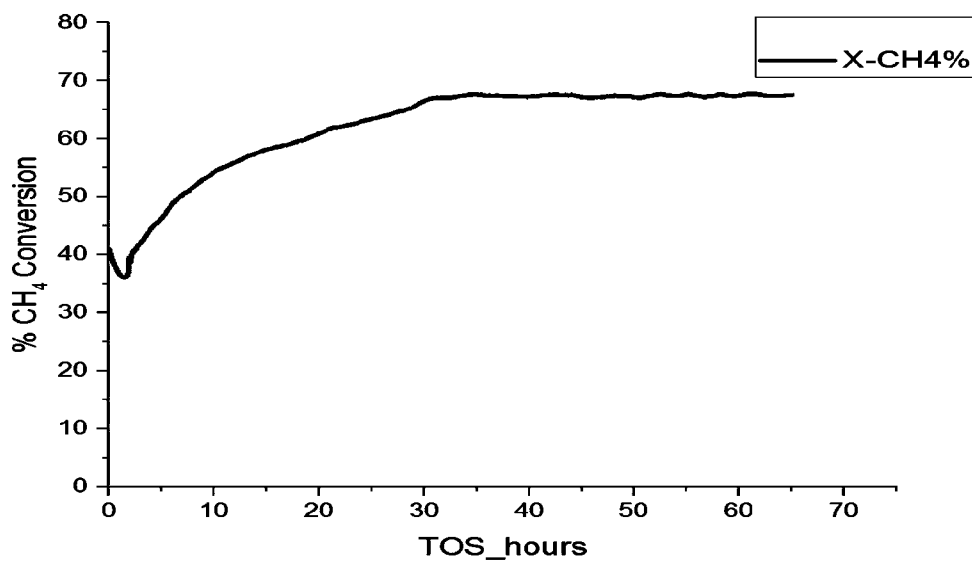


FIG. 5

5/5

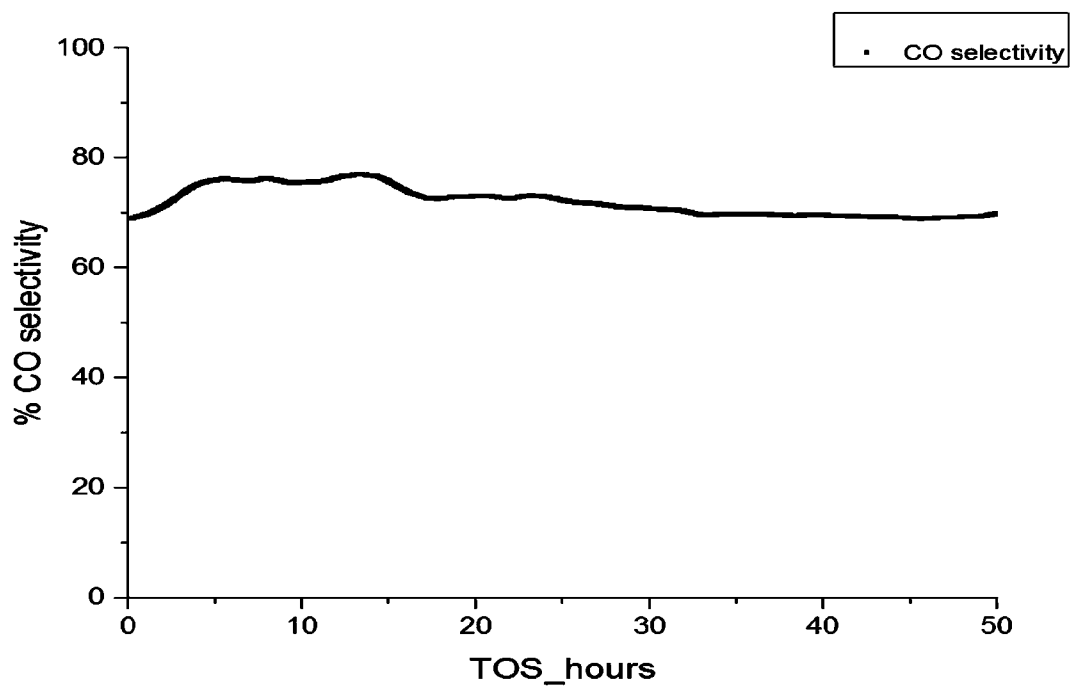


FIG. 6

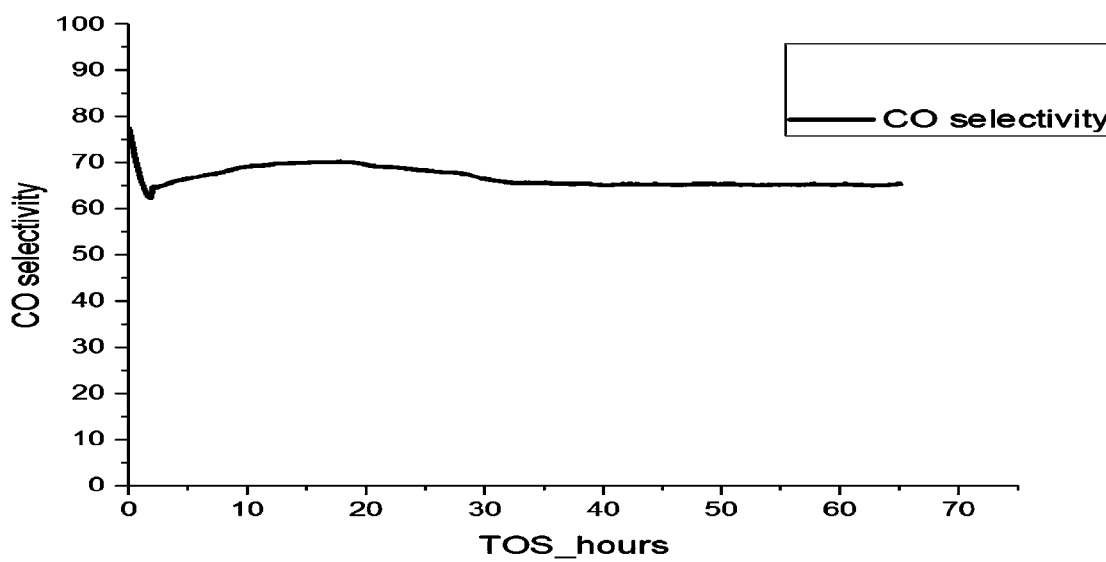


FIG. 7

# INTERNATIONAL SEARCH REPORT

International application No  
PCT/IB2019/060776

## A. CLASSIFICATION OF SUBJECT MATTER

INV. B01J23/755 B01J35/00 B01J35/04 B01J37/00 C01B3/00  
B01J23/78

ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

B01J C01C C01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Relevant to claim No.            |
|-----------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------|
| X         | <p>CAHIT BILIM: "Predicting the compressive strength of ground granulated blast furnace slag concrete using artificial neural network",<br/>ADVANCES IN ENGINEERING SOFTWARE,<br/>vol. 40, no. 5, 5 May 2009 (2009-05-05),<br/>pages 334-340, XP002797898,<br/>DOI:<br/><a href="https://doi.org/10.1016/j.advengsoft.2008.05.005">https://doi.org/10.1016/j.advengsoft.2008.05.005</a><br/>abstract<br/>page 335, left-hand column, line 15 - page<br/>336, left-hand column, line 17<br/>tables 1-6</p> <p style="text-align: center;">-----<br/>-/--</p> | <p>1-9,<br/>12-14,<br/>16,17</p> |

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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Date of the actual completion of the international search

25 February 2020

Date of mailing of the international search report

09/03/2020

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## INTERNATIONAL SEARCH REPORT

International application No

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                                                                                                                                                                                | Relevant to claim No.  |
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| X         | EP 2 623 475 A1 (SHANDONG COKING GROUP CO LTD [CN]) 7 August 2013 (2013-08-07)<br>abstract<br>example 1<br>claim 1<br>-----                                                                                                                                       | 1-5,7-17               |
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Information on patent family members

International application No

PCT/IB2019/060776

| Patent document<br>cited in search report |    | Publication<br>date | Patent family<br>member(s) | Publication<br>date |
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