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Design and Fabrication of a Reactor for Alkaline Rich Mineral Waste Carbon Sequestration

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ABSTRACT

The growing concentration of CO_2 in the environment has become one of the major concerns today due to its various harmful effects thus demanding the attention of environmentalists. This paper aims in reducing both carbon dioxide and industrial wastes in the nature. It is achieved by carbon sequestration of ladle refining furnace slag and energy optimizing furnace slag in a CSTR. Reaction parameters that are temperature, pressure, solid to liquid ratio and reaction time were varied and the optimum conditions were obtained. The extent of carbonation of each raw material was calculated and the most effective raw material was obtained by Thermal Gravimetric Analysis (TGA).

Keywords: carbon sequestration, CSTR, design, operating parameters, TGA

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INTRODUCTION

The ever-increasing alkaline rich mineral waste emission due to various anthropogenic as well as developmental activities has devastating consequences such as global warming and climate change. They are generally a result of burning of fossil fuels and by products of industrial activities such as steel and allied industries. The amount of carbon dioxide which is emitted out from the flue gases is immense and also plays a very crucial role in global warming [1]. The carbon dioxide emission and the alkaline rich waste, both should be disposed of economically and hence, this project comes into picture. It is aimed at reducing the carbon dioxide content from the flue gases and secondly alkaline rich mineral waste from the industry at the same time by making them react in a three-phase slurry stirred tank reactor. This carbonation reaction will help reduce the carbon dioxide content in the atmosphere and also reduce the amount of alkaline rich mineral waste. In this, first the amount of calcium oxide and magnesium oxide in the prepared sample of mineral wastes like steel slag, cement dust and coal fly ash is tested. Once the analysis is done, the carbonation reaction in the fabricated stirred tank reactor is started by infusing carbon dioxide into the alkaline rich waste material at some specified parameters [13]. The carbonation reaction should give stable carbonates and bicarbonates. Once the carbonation reaction is achieved, the amount of calcium and magnesium oxide is tested again in the product and the difference in its presence from the earlier analysis is observed [2]. This will give the efficiency of carbonation and hence the result. Highest efficiency of carbonation is observed and the fabrication of an agitator is expected to enhance the conversion. This will serve the purpose of various industries in meeting the environmental regulations regarding waste and its disposal and reduce the carbon content in the atmosphere.

DESIGN

Chemical reactors are vessels designed to contain a chemical reaction. Reactors can be classified as stirred tank reactor, tubular reactor, packed bed reactor and fluidized bed reactor. A Continuous Stirred Tank Reactor has been used for the carbonation reaction [3]. Construction of material used in fabrication is Stainless Steel-316. The reactor consists of a cylindrical shell of 10mm thickness, 87mm inside diameter and 115 mm height. The reactor is enclosed by a flat head and has a three-blade impeller for agitation. The entire reactor setup is mounted on a skirt support. Mathematical calculations are done for verification of the design of the reactor. The final design is also drafted for clear understanding.

Thickness of the Shell

Length of the reactor (L) =11.5cm
Inside Diameter (Di) = 8.7cm
Maximum Pressure= 4kgf/cm^2 (gauge)
Atmospheric Pressure, (P)= 4+1.01336
                =5.01336 kgf/cm^2
Taking 110% safety factor, P= 5.01336×1.1
                = 5.5146

Joint Efficiency (J) =0.8 (spot radiography)
Allowable stress (f) =1300 kgf/cm^2 (for stainless steel)
Corrosion Resistance (C) = 0 (Since, stainless steel is used here corrosion resistance is not required)

$$t = \frac{P \times D_i}{2fJ - D_i} + C \qquad (1)$$

$$t = \frac{5.01336 \times 87}{(2 \times 1300 \times 0.8) - 87} = 0.2188mm \quad (2)$$

Thus, thickness of shell is 0.2188mm. Thickness cannot be this low because such a thin material will not be stiff and it will bulge out. Thus, 10mm thickness is optimum.

Equivalent Diameter (De)
=87mm=0.087cm (assumed De=Di)
Allowable stress (f) = 1300 kgf/cm^2 = 12753 × 104 N/m^2
Pressure (P) = 5.01336 kgf/cm^2 = 49.81×104 N/m^2

$$t = Cp \times D_e \sqrt{\frac{P}{f}} \qquad (3)$$

$$t = 0.45 \times 0.087 \sqrt{\frac{49.81 \times 10^4}{12753 \times 10^4}} = 2.4mm \qquad (4)$$

Thus, thickness of head is 2.4mm. Since this thickness will be difficult to fabricate and also stiffness will be low, so higher value is used. Thus, 10mm thickness is optimum.

Thickness of Jacket

Diameter of Jacket (Dj) =8.7+1+1+1.5+1.5
              = 13.7cm=137mm

Radius of Jacket (R) = 137/2= 68.5mm
Pressure (P) = 5.01336 kgf/cm^2
Allowable Stress (f) = 1300 kgf/cm^2

$$t = \frac{P \times R}{fJ - 0.6P} \qquad (5)$$

$$t = \frac{5.01336 \times 68.5}{(1300 \times 0.8) - (0.6 \times 5.01336)} = 0.33mm \qquad (6)$$

Thus, thickness of jacket is 0.33mm. Since this is very difficult to fabricate and the stiffness will be less this value is not used. Thus, the 15cm thickness is optimum.

Agitator Calculations

[1]. Agitator thickness
The empirical relations are:

$$\frac{D_a}{D_t} \geq \frac{1}{3}, \qquad (7)$$

$$\frac{H}{D_t} = 1 \qquad (8)$$

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Where Da is the diameter of the agitator blade, Dt is the diameter of the reactor and H is the height of the reactor. For the given reactor:

$$\frac{D_a}{D_t} = \frac{8}{8.7+2} = 0.747 \qquad (9)$$

Thus, $\frac{D_a}{D_t} > \frac{1}{3}$

$$\frac{H}{D_t} = \frac{11}{10.7} \approx 1$$

Thus, both the empirical relations are satisfied. Therefore, diameter of agitator 8cm and thickness of 1cm is optimum.
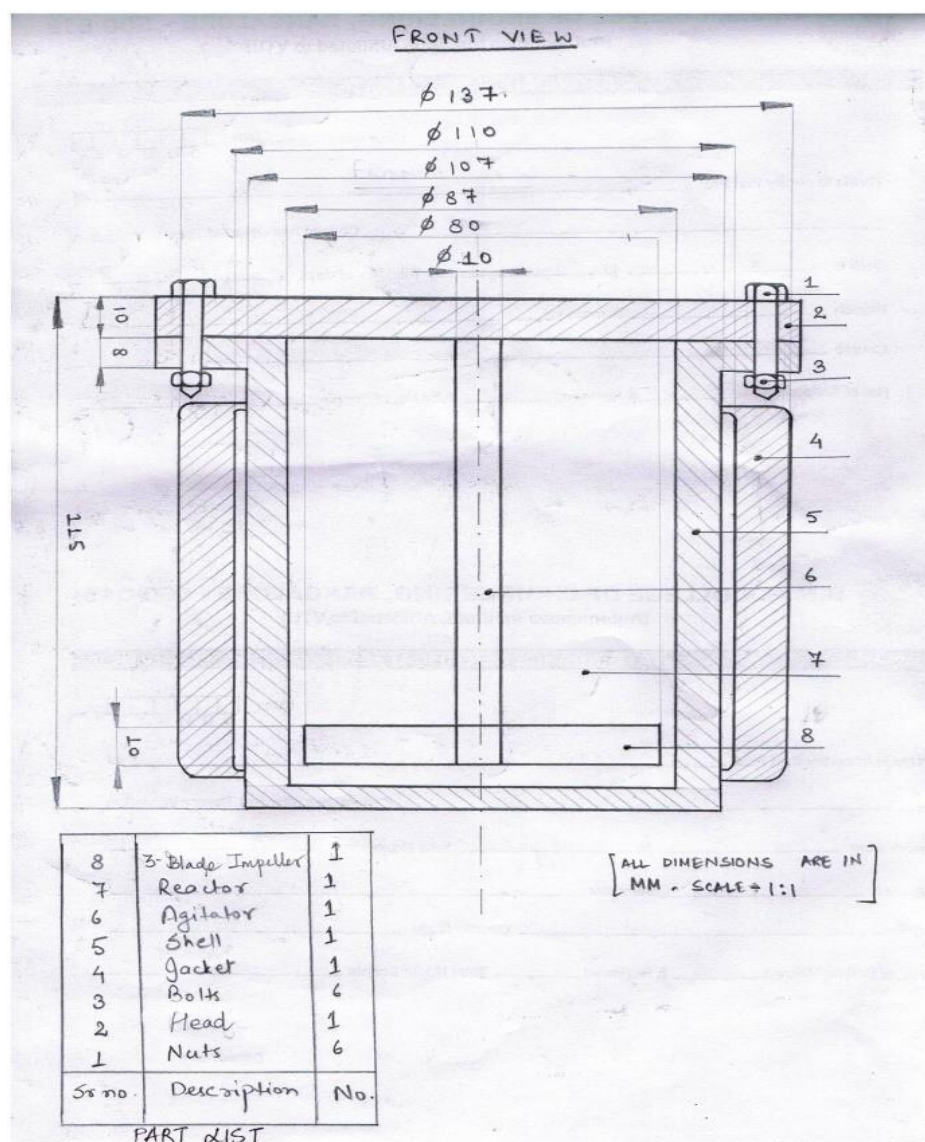
[2] Agitator power calculation

When NRe <   (10)
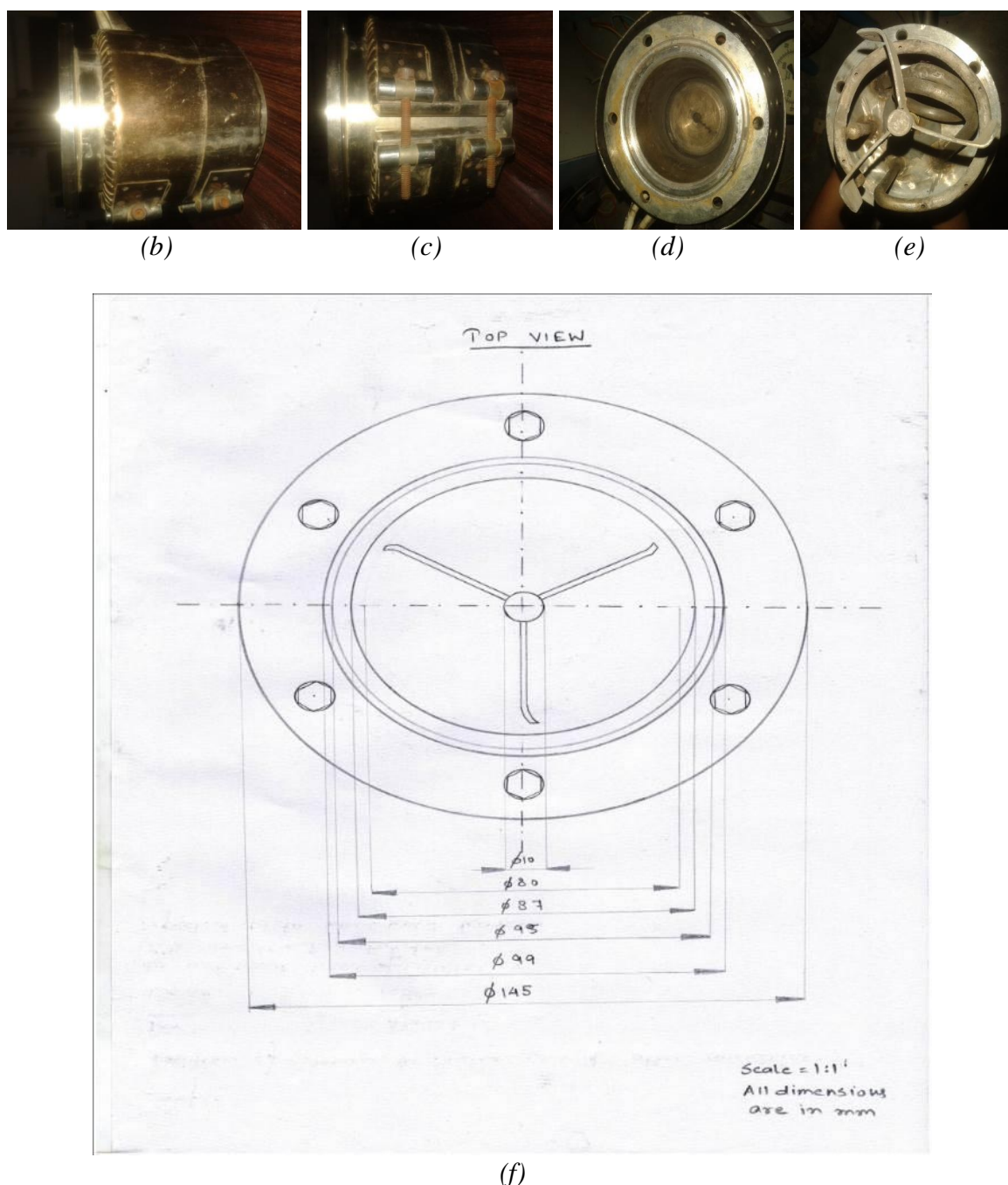
Then KL = 41

$$P = K_L n^2 D_a^3 \mu \qquad (11)$$

where 'n' is the rotations per minute of the agitator, 'μ' is the viscosity of the agitated fluid and 'KL' is the coefficient used for lower Reynold's number [4].

$$P = 41 \times \left(\frac{26}{60}\right)^2 \times 0.08^3 \times 0.08422 = 0.332 mW$$

$$(12)$$

Therefore, power consumed is 0.332 milliwatts

(a)

(b)   *(c)*   *(d)*   *(e)*

(f)

Fig. 1. *(a) Sectional front view of the reactor. (b) The jacket surrounding the shell. (c) Shell and the entire vessel. (d) The three-blade paddled agitator. (e) The insides of the vessel without the head. (f) The sectional top view of the reactor.*

MATERIALS AND METHODS
Procurement of Raw Materials

Steel Slag: It is the industrial waste generated in the iron and steel industry. It is produced in the industry during the separation of molten steel from the impurities. Initially it will be in the molten liquid state which upon solidification on cooling results in complex mixture of silicates and oxides. The steel usually consists of 30 to 40% CaO and 5–10% MgO in its chemical composition. The chemical composition steel slag is alkaline waste with the pH ranging between 8 to 10. Due to this chemical composition and natural alkalinity steel slag proves to be a possible feedstock for mineral carbon sequestration. Two types of steel slag were

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procured from Kalyani Steels Ltd. Energy Optimizing Furnace (EOF), and Ladle Refining Furnace (LRF).

Processing of Raw Materials
The raw materials procured and processed are, steel slag and coal fly ash for carbonation reaction. Two types of steel slag were obtained from the industry, EOF and LRF. The raw materials obtained were first passed through a jaw crusher. Jaw crusher uses compressive force to reduce large rocks into smaller rocks. These smaller rocks were then passed through ball mill. Ball mill was being used to grind the small rocks to fine homogenous rock dusts. The ball mill was operated at a speed of 40 rpm for 30 minutes [5]. The media used for grinding in this particular ball mill was stainless steel balls. The product obtained from ball mill was then passed through 90 micrometer sieve. The sieving process was carried out in an automatic sieve shaker. The final samples obtained after grinding were dried at 50ºC in a hot air oven for 2 hours. The dried product was kept in air tight containers. These raw materials were then tested for their calcium oxide and magnesium oxide content.

(a)   *(b)*

Fig. 2. *This indicates (a) raw slag obtained from the steel industry; (b) grinded, screened and dried slag.*

Preparation of the Solution for Steel Slag (EOF & LRF)
Drying: Some amount of sample solution is taken on a petri dish and spread evenly and homogenized for better and uniform drying. It is covered with another petri dish and put in an oven at 105°C for 2 hours for complete drying. Further, the sample was cooled and placed in a desiccator which has silica gel in order to absorb remaining moisture and dry it completely.

2) Fusing: The fusing is done to remove silica from the sample.1 gm of the slag sample is accurately weighed in a platinum crucible. First sodium carbonate is added to the crucible containing the slag (approximately 3 g) and then mixed thoroughly. A total of 7 g of sodium carbonate is used for covering the sample so as to prevent any splashing of the sample slag while heating in the muffle furnace. The sample was then kept in a muffle furnace at a temperature of 1000°C for half an hour. The temperature is raised slowly until frothing ceases. To prevent splashing, the crucible was covered at the top with a lid. Occasional swirling is done to ensure complete mixing [6].

3) Single Baking: After half an hour the platinum crucible along with the lid is taken out of the furnace and immersed in cold water to cool it. 100 ml of hot water was poured in a beaker. After some subsequent amount of cooling is done by quenching the melt by immersing the bottom half of the hot crucible in cold water, then the crucible was placed inside the hot water beaker. This is done to scrape out the entire content of the crucible. Few drops of absolute alcohol was added to this beaker along with 30 ml of concentrated hydrochloric acid. This was done to scrape out the content totally from the crucible and to completely dissolve it. Sodium carbonate was completely fused in the solution. The entire solution is stirred properly with a glass rod to achieve uniform and complete mixing. The whole setup was heated on a coil stove to remove and dissolve the remaining particles from the crucible and the lid. The lid and crucible are washed with distilled water to remove any remains on the same. The beaker was placed on a water bath at 100ºC and allowed to dry until clear precipitate was formed for 18-20 hours. After it is completely dried, 20 ml of HCl and 75 ml of hot water and mixed thoroughly [7].

4) Filtration: The solution is filtered using 40 Whatman paper. The filtrate is the prepared solution and the residue contains silica remains. The lumps are dissolved using 1% HCl in water (4ml of HCl in 400ml of water) for both the samples. The beaker containing the crystal solution is completely cleaned by distilled water and poured over the filter paper.

Fig. 3. *The two different sample solutions.*

Preparation of Buffer Solution
70 g of ammonium chloride was added in 570 ml of ammonia solution (sp. gravity-0.9). After this dissolution is achieved perfectly, it is made upto 1 liter with distilled water.

Preparation of 0.01 M EDTA Solution
3.722 g of EDTA salt is taken and dried in a hot air oven at 105°C and subsequently kept in a dessicator with silica gel to absorb any traces of moisture for four hours. The dried salt is then taken and dissolved in water in a volumetric flask and the volume is made upto 1 liter and it is allowed to stand for one full day and mixed well. This gives us 0.01M EDTA solution. For standardization, it is titrated against 0.01M Zinc solution. It was observed that 10ml of 0.01M EDTA solution consumed the exact same volume of the zinc solution of equal molarity.

Determination of CaO and MgO in Each Sample
1) CaO Determination: The solution was prepared and 10 ml of solution was taken in a 250 ml conical flask. In this solution 5 ml of 1:1 glycerol was added with constant stirring followed by 5 ml of diethyl amine. Further, 10 ml of 4 N NaOH was added to adjust the pH to 12. This was followed by the addition of 50 mg of Patton's reader indicator and 50 ml of distilled water. This final solution was titrated against 0.01 M EDTA where the color change observed was from wine red to clear blue [7].

2) MgO Determination: 10 ml of the prepared solution was taken to which 5 ml of triethanolamine and 20ml of ammonia buffer solution of pH 10 was added with constant stirring. This was followed by the addition of 50 mg of solid thymol pthalexone indicator and approximately 50 ml of distilled water was added. This final solution was then titrated against 0.01 M EDTA solution and the titer value gives a sum of MgO and CaO content in the solution. Thus, MgO concentration was obtained by subtracting the titer value of CaO from the total titer value [7].

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Assembling of the Reactor

Carbonation experiments were performed in a reactor of known volume. The reactor is made with thick stainless-steel material which has facility to incorporate carbon dioxide cylinder to carry out the carbonation. The reactor consists of a core cylindrical container to carry out carbonation, a temperature controller to monitor temperature, an aluminium coil for heating, a cooling facility, a silicon rubber gasket to maintain air tight condition, a lid which has facilities to have cooling system, carbon dioxide inlet, pipe for letting out exhaust gases, sockets to incorporate sensors to monitor temperature, gauge to monitor pressure inside the reactor and most important of all is the installation of an agitator with a four blade turbine impeller which is expected to enhance the efficiency of the reactor. The inlet pipe of the cooling system is connected to tap so that water passes and cools the reactor and outlet is let into the drain. The carbon dioxide is passed through the carbon dioxide cylinder by controlling valves. The heat in the reactor is produced by the coil. The cylindrical core is placed in an aluminium jacket.
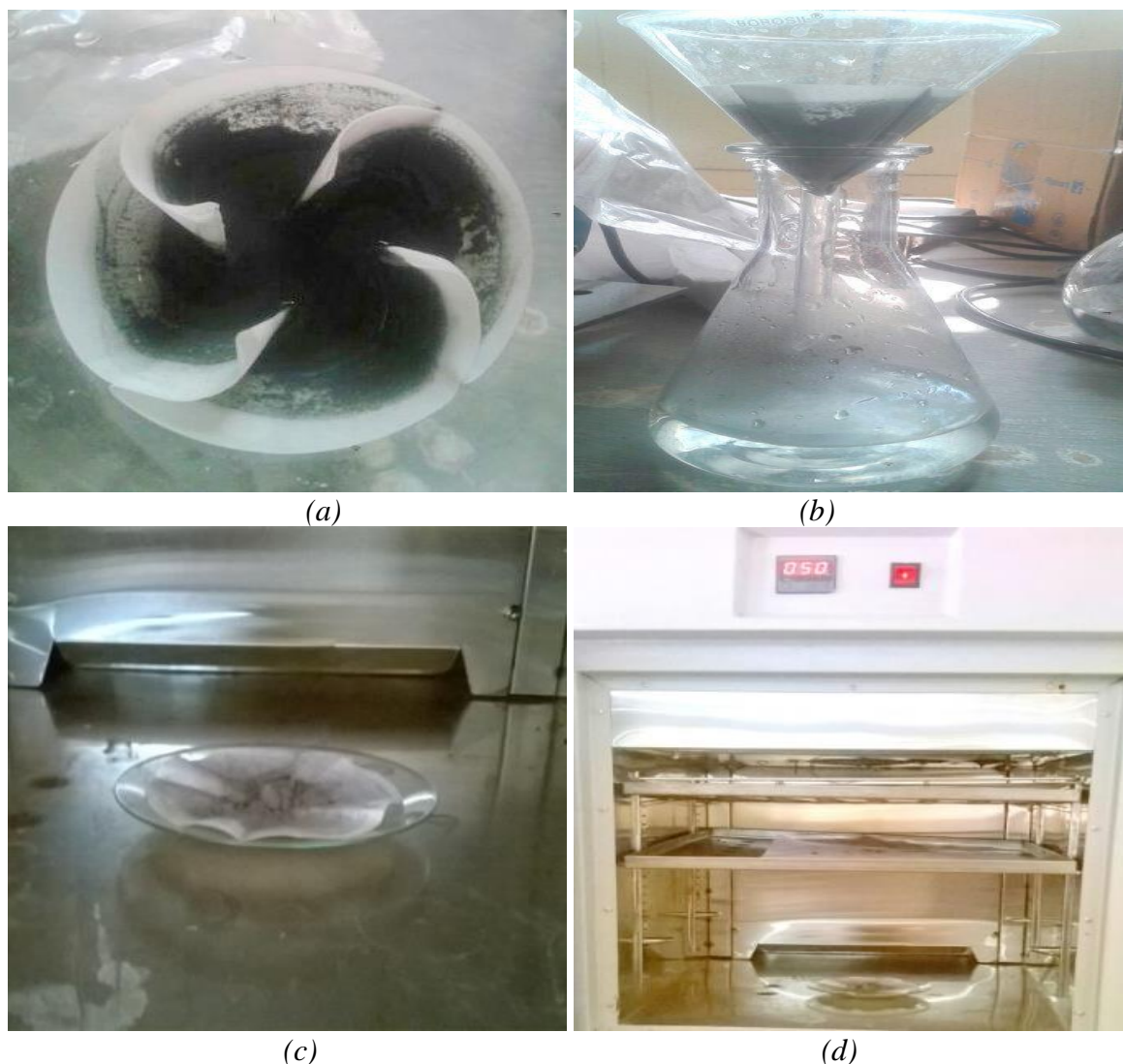
Carbonation

The carbonation experiments were carried out in the reactor by varying different parameters. One parameter was varied at a time keeping the remaining parameters constant. 10g of 90 microns size, moisture free sample was taken and mixed with distilled water according to the prior chosen solid to liquid ratio to form the slurry which was poured into the reactor. The reactor was then sealed with an air tight lid and was then heated to the desired temperature. Once the desired temperature was reached, the carbon dioxide was bubbled through the slurry for the desired reaction time using appropriate regulating valves. Once the reaction time elapsed, the reactor was depressurized by opening the exhaust valve. The reactor was then cooled to 30°C by passing cold water through the inlet of the cooling system. The slurry was filtered on a 40 number Whatman paper. The carbonated sample retained on the filter paper was dried in the hot air oven at 50°C overnight. The dried carbonated sample was then stored in air tight containers until test to know the extent of carbonation [8].

Fig. 4. *Photograph of the assembled CSTR with connections to pressure gauge, temperature controller and pressure relief valve. The cooling coils are also used to control the temperature.*

(a)   *(b)*

(c)   *(d)*

Fig. 5. *(a) Filtration of the carbonated product, (b) residue after filtration, and (c) heating of the residue at 50ºC in a hot air oven (d) dried product.*

Estimation of Extent of Carbonation
Thermal gravimetric analysis (TGA) was carried out on the carbonated sample to know the extent of carbonation. According to this method, the change in mass at temperatures of 500°C and 1000°C indicated the percentage of carbonates in the sample. TGA results gave the amount of change in weight as a function of temperature. Carbonate decomposition occurred at these temperatures. Hence the change in weight or the loss in weight gave the extent of carbonation. The carbonated samples were weighed in a silica crucible and were heated to temperatures of 500°C for 15 minutes and the loss in weight was taken as the organic fraction of carbon dioxide which indicated the presence of carbonates of magnesium. The same sample was again heated for 15 minutes at 1000°C and the loss in weight was noted. This fraction of weight loss at 1000°C indicated the inorganic carbon dioxide i.e. the presence of carbonates of calcium. A clean silica crucible was weighed empty and then 1 gram of carbonated sample was placed in it and the sample was heated for 15 minutes at temperature of 500 and 1000°C respectively [13]. The loss in weight at each of the temperatures indicated the extent of carbonation. The alkaline rich materials containing fair amount of CaO and MgO were used for the sequestration

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of carbon dioxide. The various parameters that were varied and checked for their influence on carbonation were reaction time, pressure, temperature and liquid to solid ratio. The extent of carbonation i.e.

the conversion of Ca and Mg oxides into the carbonates was tested using thermogravimetric analysis (TGA). The influence of various process variables are listed further [9].

***Fig. 6.** 1 g of the residue heated to 500°C and 1000ºC in a muffle furnace.*

Parameters to be Varied

1) Reaction Time: The reaction time is the time duration for which the CO_2 remains in contact with the slurry in the reactor at the predetermined temperature and pressure at 50ºC and 1 kgf/cm^2. It is the time taken by the gas to interact with the slurry. The aim was to vary the reaction time between 1 hour to 3 hours and the behavior of carbonation was to be tabulated. Also, the predetermined parameter such as liquid solid ratio was maintained at 10. Also, the particle size was kept steady at 90 micrometers [10].

2) Temperature: Temperature was another important variable where the slurry was heated to desired temperature and once it reached the desired temperature CO2 was passed through the slurry. Until the desired reaction time elapsed, the temperature was maintained by operating the exhaust gas valve and cooling systems.

3) Liquid to solid ratio: It is the ratio between the amount of water to the amount of alkaline waste. In aqueous path of mineral carbonation, water serves as a medium where the Ca and Mg oxides dissolve in water and then react with CO2. In this study a wide range of liquid to solid ratio were selected and the carbonation was carried out. The Liquid/Solid ratio was varied from 5 to 10 and the experiments were carried out.

4) Pressure: Pressure refers to the pressure of CO_2 inside the reactor. The reactor pressure was maintained by operating the inlet and exhaust gas valves accordingly. Throughout the reaction time, the pressure in the reactor was maintained at the desired constant pressure by operating the necessary valve. In this study the pressure may be varied between 1 and 3 kg/cm^2 and its influence on the extent of carbonation was observed.

RESULTS AND DISCUSSION
Determination of CaO
1) Ladle Refined Furnace Slag
10 ml of the prepared solution of LRF was titrated against 0.01M EDTA. The amount of CaO present in the sample is determined by applying equation 1 and the result is calculated as given in Equation 2.
Titre Value: 24 ml
Formula:

$$\%CaO = \frac{Molarity\ of\ EDTA \times Mol.WT\ of\ CaO \times Make-up\ Vol \times V \times 100}{W \times 1000 \times volume\ of\ sample\ taken} \tag{1}$$

where V=volume of EDTA used in ml and W=weight of sample.

Calculation:

$$\%CaO = \frac{0.01 \times 56.08 \times 250 \times 24 \times 100}{1 \times 1000 \times 10}$$
$$=33.65\% \tag{2}$$

2) Energy Optimizing Furnace Slag
10 ml of the prepared solution of EOF was titrated against 0.01M EDTA. The amount of CaO present in the sample is determined by applying equation 3 and the result is calculated as given in Equation 4.
Titer Value: 15.7 ml
Formula:

$$\%CaO = \frac{Molarity\ of\ EDTA \times Mol.WT\ of\ CaO \times Make-up\ Vol \times V \times 100}{W \times 1000 \times volume\ of\ sample\ taken} \tag{3}$$

where V=volume of EDTA used in ml and W=weight of sample

Calculation:

$$\%CaO = \frac{0.01 \times 56.08 \times 250 \times 15.7 \times 100}{1 \times 1000 \times 10}$$
$$=22.01\% \tag{4}$$

Table 1. *Content of CaO in the raw material.*

Material used	Percentage of CaO (%)
Ladle refining furnace slag (LRF)	33.65
Energy optimizing slag (EOF)	22.01

Determination of MgO
1) Ladle Refining Furnace
10 ml of the prepared solution of LFR was titrated against 0.01M EDTA. The amount of MgO present in the sample is determined by applying equation 5 and the result is calculated as given in Equation 6.
Titer Value: 24.5 ml
Formula:

$$\%MgO = \frac{Molarity\ of\ EDTA \times Mol.WT\ of\ MgO \times Make-up\ Vol \times (V_1-V) \times 100}{W \times 1000 \times volume\ of\ sample\ taken} \tag{5}$$

where V=volume of EDTA used in ml for CaO titration and V1 is the volume consumed for MgO titration. W=weight of sample.

Calculation:

$$\%MgO = \frac{0.01 \times 40.32 \times 250 \times (24.5-24) \times 100}{1 \times 1000 \times 10}$$
$$=0.5\% \tag{6}$$

2) Energy Optimizing Furnace Slag:
10 ml of the prepared solution of EOF was titrated against 0.01M EDTA. The amount of MgO present in the sample is determined by applying equation 7 and the result is calculated as given in Equation 8.
Titer Value: 16.4 ml
Formula:

$$\%MgO = \frac{Molarity\ of\ EDTA \times Mol.WT\ of\ MgO \times Make-up\ Vol \times (V_1-V) \times 100}{W \times 1000 \times volume\ of\ sample\ taken} \tag{7}$$

where V=volume of EDTA used in ml for CaO titration and V1 is the volume consumed for MgO titration. W=weight of sample.

Calculation:

$$\%MgO = \frac{0.01 \times 40.32 \times 250 \times (16.4-15.7) \times 100}{1 \times 1000 \times 10}$$
$$=0.7\% \tag{8}$$

Table 2. *Content of MgO in the raw material.*

Material used	Percentage of MgO (%)
Ladle refining furnace slag (LRF)	0.5
Energy optimizing slag (EOF)	0.7

Estimation of Extent of Carbonation
Model Calculation:
Loss in weight at 500°C = (Empty weight of crucible + 1g slag - Weight at 500°C)

Loss in weight at 1000°C = (Empty weight of crucible + 1g slag - Weight at 1000°C)

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%MgO carbonated = (Loss in weight at 500°C) ×100

%CaO carbonated = (Loss in weight at 1000°C) × 100

1) Effect of Reaction Time

The reaction time is the time duration for which CO2 remains in contact with the slurry in the reactor at the pre-determined temperature and pressure it is the time taken by the gas to interact with the slurry. The reaction time was varied between one to five hours and the behavior of carbonation is as tabulated in Table 3 for LRF and Table 4 for EOF. To check the influence of reaction time solid to liquid ratio was maintained at 10, the temperature at 50°C and the pressure of CO2 was maintained at 1 kg/cm² for LRF, whereas for EOF, all parameters remained the same except temperature which was set at 30°C. The optimized result was observed at a reaction time of 4 hours for LRF and 3 hours for EOF and is highlighted in the tables. The effect of reaction time on carbonation of CaO and MgO are represented graphically in Figure 6(a) and (b) for LRF and EOF, respectively. It also shows the comparison of CaO and MgO conversion at different reaction times.

Table 3. Effect of reaction time on carbonation for LRF.

Reaction time in hours	Weight of crucible + sample (gm)	Weight at 500°C (gm)	Weight at 1000°C (gm)	Carbonation of MgO	Carbonation of CaO
1	17.1	17.08	17.05	2%	5%
2	17.12	17.06	16.98	6%	14%
3	17.13	17.06	16.96	7%	17%
4	17.12	17.06	16.96	6%	16%
5	17.12	17.06	16.98	6%	14%

Table 4. Effect of reaction time on carbonation for EOF.

Reaction time in hours	Weight of crucible + sample (gm)	Weight at 500ºC (gm)	Weight at 1000ºC (gm)	Carbonation of MgO	Carbonation of CaO
1	72.58	72.48	72.39	10%	19%
2	72.58	72.46	72.35	12 %	23 %
3	72.58	72.40	72.28	18%	30%
4	72.58	72.36	72.26	22%	32%
5	72.58	72.36	72.25	22%	31%
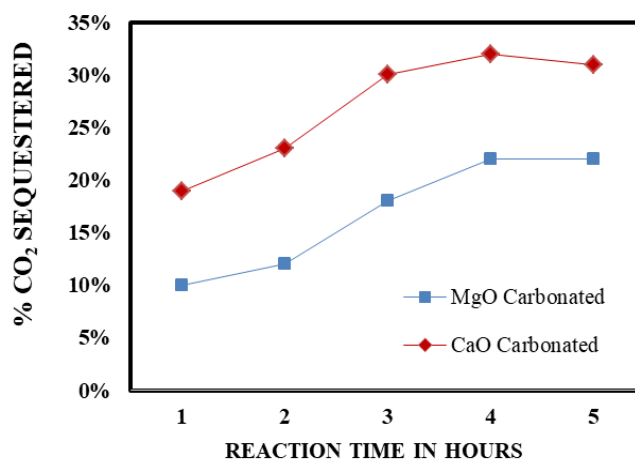
(a)
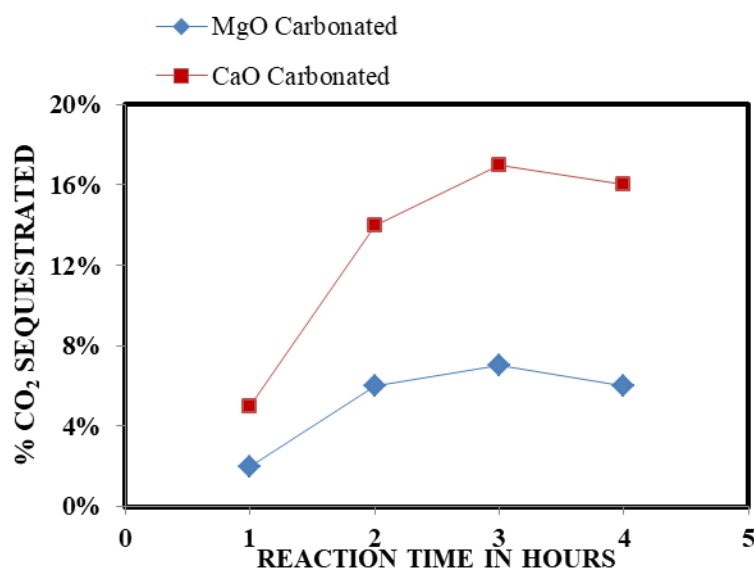
(b)

Fig. 7. *Relation between percentage of carbon dioxide sequestrated and reaction time for (a) LRF, (b) EOF.*

2) Effect of Temperature
Temperature is another important process variable. The slurry is heated to the desired temperature and when it reaches the desired temperature the carbon dioxide gas is bubbled through the slurry. Until the decided reaction time elapses the temperature is maintained by the cooling system. The variation in the extent of carbonation at various temperatures is as tabulated in Table 5 for LRF and Table 6 for EOF. Here, for LRF and EOF the solid to liquid ratio was maintained at 10, reaction time at 1 hour and pressure at 1 kg/cm^2. The optimized result was observed at a temperature of 50ºC for LRF and 40ºC for EOF and is highlighted in the tables. The effect of temperature on carbonation of CaO and MgO are represented graphically in Figures 7(a) and (b) for LRF and EOF, respectively. It also shows the comparison of CaO and MgO conversion at different reaction times.

Table 5. *Effect of temperature on carbonation for LRF.*

Temperature (ºC)	Weight of crucible + sample (gm)	Weight at 500ºC (gm)	Weight at 1000ºC (gm)	Carbonation of MgO	Carbonation of CaO
30	17.18	17.10	17.06	8%	12%
40	64.9	64.81	64.76	9%	14%
50	72.58	72.48	72.39	10%	19%
70	17.15	17.11	17.06	4%	9%
90	17.13	17.12	17.03	1%	10%

Table 6. *Effect of temperature on carbonation for EOF.*

Temperature (°C)	Weight of crucible + sample (gm)	Weight at 500°C (gm)	Weight at 1000°C (gm)	Carbonation of MgO	Carbonation of CaO
30	17.10	17.08	17.05	2%	5%
40	17.11	17.06	16.99	5%	12%
50	17.12	17.08	17.02	4%	10%
60	17.12	17.08	17.04	4%	8%
70	17.12	17.10	17.05	2%	7%

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Table 10. Effect of pressure on carbonation for EOF.

Pressure (kg/cm²)	Weight of crucible + sample (gm)	Weight at 500°C (gm)	Weight at 1000°C (gm)	Carbonation of MgO	Carbonation of CaO
1	17.10	17.08	17.05	2%	5%
2	17.14	17.10	17.05	4%	9%
3	17.12	17.07	16.98	5%	14%
4	17.14	17.11	17.04	3%	10%

Empty weight of the crucible= 16.13g
Weight at 500°C= 17.00 g
Weight at 1000°C=16.76g
Loss in weight at 500°C = (17.13–17.00) = 0.13g
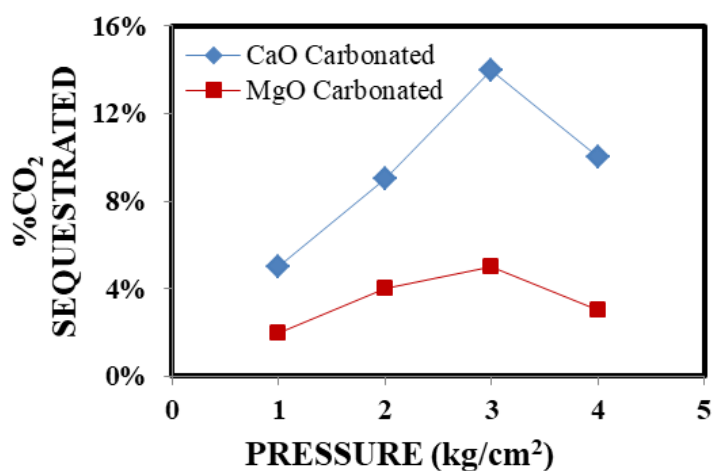Loss in weight at 1000°C = (17.13–16.76) = 0.37g
%MgO Carbonated= 0.13
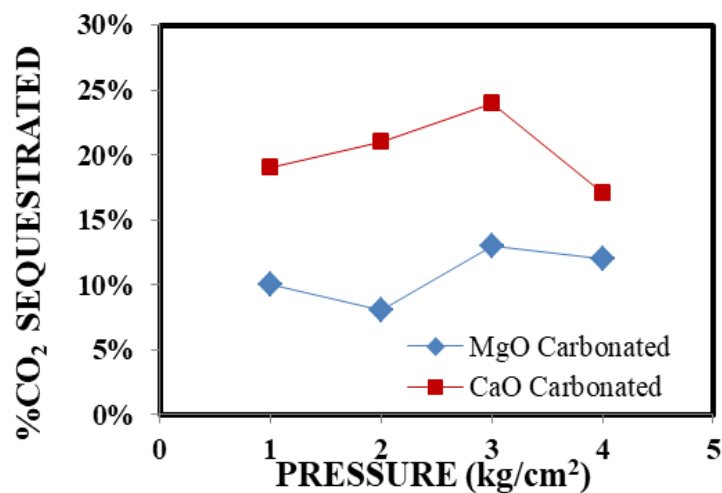%CaO Carbonated = 0.37 x 100= 37%

The extent of CaO carbonated is 37% and MgO carbonated is 13%.

Energy Optimizing Furnace Slag:
This sample was subjected to carbonation at the optimum conditions of temperature 40°C, pressure of 3kgf/cm², for reaction time 3 hours and liquid to solid ratio of 12.

(a)

(b)

Fig. 10. *Relation between percentage of carbon dioxide sequestrated and pressure for (a) LRF, (b) EOF.*

5) Carbonation at optimum conditions

From the systematic experimentation the various process variables have been fixed at their optimum values. The carbonation at the optimum conditions is an important assessment.

Ladle Refining Furnace Slag:

This sample was subjected to carbonation at the optimum conditions of temperature 50ºC, pressure of 3kgf/cm^2, for reaction time 4 hours and liquid to solid ratio of 10.

Empty weight of the crucible: 16.13g

Weight at 500ºC=17.02g

Weight at 1000ºC= 16.88g

Loss in weight at 500ºC= (17.13–17.02) =0.11g

Loss in weight at 1000ºC= (17.13–16.88) = 0.25 g

%MgO Carbonated=0.11×100=11%

%CaO Carbonated=0.25× 100=25%

The extent of CaO Carbonated is 25% and MgO Carbonated is 11%.

CONCLUSION

The experiments were performed taking into consideration all the parameters such as temperature, reaction time, liquid to solid ratio and pressure for Ladle Refining Furnace slag and Energy Optimizing Furnace slag. It was observed that the efficiency of the reactor was optimum when carbonation was done for four hours at 50°C, liquid to solid ratio of 1:10 and pressure of 3 kg/cm^2 for ladle refining furnace slag. Similarly, optimized condition for energy optimizing furnace slag observed is: temperature – 40ºC, pressure – 3 kgf/cm^2, reaction time – 3 hours and liquid to solid ratio of 12. The optimum reactions had carbonation efficiency as follows:

Table 11. *Carbonation efficiencies of LRF and EOF.*

Material	CaO extent	MgO extent
LRF	37%	13%
EOF	25%	11%

By these results, it can be concluded that LFR has greater carbonation efficiency in comparison to EOF. This experiment can further be repeated by considering biomass as a raw material and with varying particle sizes and agitator rotation speeds. Finally, the carbon and energy footprints can be scaled by studying the surplus of carbon credits that could be achieved by using this method of carbon dioxide capture. This surplus gives the net profit. The converted carbonates and bicarbonates can be further processed to make bricks or for construction of roads. It can also be stored in landfills. Under any of these circumstances, the product is less harmful and causes no or very less harm to the environment [15].

REFERENCES

[1] G.J. Olivier Jos, G.J. Maenhout, M. Muntean, J.A.H.W. Peters. *Trends in global CO2 emissions: 2013 Report*. PBL Netherlands Environmental Assessment Agency, 2013, 6–12p. Unpublished.

[2] C. Stewart, M.A. Hessami.. A study of methods of carbon dioxide capture and sequestration – the sustainability of photosynthetic bioreactor approach, *J Enconman.* 2005; 405–15p.

[3] S.I. Plasynski, Z.Y. Chen. *Review of CO2 Capture Technologies and Some Improvement Opportunities*. US DOE National Energy Technology Laboratory, Science Application International Corporation, PCS acsfuel publication; 2012, Vol. 45-4, 644–911.

[4] M. Mazzotti, J.C. Abanades, R. Allam, K.S. Lackner, F. Meunier, E. Rubin, J.C. Sanchez, Yogo, R. Zevenhoven. Mineral carbonation and industrial uses of carbon dioxide, *IPCC Special Report on Carbon Dioxide Capture and Storage.* 321–60P. unpublished.

[5] K. Keller, Z. Yang, M. Hall, D.F. Bradford. Carbon dioxide sequestration: when and how much?" Centre for economic policy studies working paper no-94 Princeton University-2003, pp. 2-18; unpublished.

[6] IS 1727-1967.

[7] IS 4032-1985.

[8] W.L. McCabe, J.C. Smith, P. Harriot. *Unit Operations of Chemical Engineering.* 7th Edn., Mc Graw Hill.

[9] https://en.wikipedia.org/wiki/Carbon _sequestration.,19/06/2016.

[10] http://www3.epa.gov/climatechange/ ccs/index.html, 19/06/2016.

[11] http://www.pyrometallurgy.co.za/Mo ltenSlags2004/031-Seetharaman.pdf,19/06/2016.

[12] http://www.euroslag.com/products/pr operties/, 19/06/2016.

[13] W.J.J. Hujigen, R.N.J. Comans, G.J. Witkamp. Mineral CO_2 sequestration by Steel slag carbonation, *J Environ Sci Technol*. 2005; 29: 9676–82p.

[14] M. Mun, H. Cho. Mineral carbonation for carbon sequestration with industrial waste, *Energy Proc*. 2013; 37: 6999–7005p.

[15] Y.S. Pan, E.E. Chang, P.C. Chiang. CO_2 capture by accelerated carbonation of alkaline wastes: a review on its principles and applications, *Res Gate Aerosol Air Qual Res*. 2012; 772–89p. unpublished