Restoration of Compressive Strength of Recycled Gypsum Board Powder.

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ABSTRACT

Reversal of the state of hydration of waste gypsum powder was carried out via calcination to enable the reuse of the powder for gypsum board manufacturing. Having confirmed the transformation of hemihydrate to dihydrate in the forward process of the manufacturing, using gravimetric analysis, attempts were made at reversing the dihydrate back to hemihydrates. At every temperature of calcination (120°C, 140°C, 160°C, 180°C, and 200°C), color variation, moisture content and compressive strength measurements were carried out. Analysis of the results obtained showed the best recovery of strength at 160°C. At this calcination temperature, the compressive strength of the mold for the 100% recycled powder (using standard steel mold with dimension 100mm height by 50mm diameter) was obtained to be $273kN/m^2$. This rose to 285 kN/m^2, when the recovered powder was blended with 20% of fresh POP while 30% blend gave a compressive strength of 301 kN/m^2 which is about three-quarters of the strength of the fresh raw POP. The crystal white color of the original powder was also restored at calcination temperatures of 120°C and above.

(Keywords: *gypsum board, dry wall, Plaster of Paris, calcinations, restoration, compressive strength, recycling, manufacturing*)

INTRODUCTION

Gypsum is a very soft mineral composed of calcium sulphate dihydrate, with the chemical formula $CaSO_4.2H_2O$ (Cornellis et al., 1985). Plaster of Paris (POP) is a calcium sulphate hemihydrate ($CaSO_4.1/2H_2O$) derived from gypsum, a calcium sulphate dihydrate, by firing this mineral at relatively low temperature and then reducing it to powder (Taylor, 1990). Calcination of the gypsum at higher temperature produces different types of anhydrites of $CaSO_4$.

Calcium sulphate exists in various forms. In the form of γ-anhydrite, it is used as a dessicant. It is also used as a coagulant in several products. In the natural state, unrefined calcium sulphate is a translucent, crystalline white rock. When sold as a color-indicating variant under the name Drierite®, it appears blue or pink due to impregnation with cobalt chloride which functions as a moisture indicator. The anhydrous form occurs naturally as β-gypsum. The hemi-hydrate is better known as Plaster of Paris while the dihydrate occurs naturally as gypsum (Taylor, 1990).

Alpha and Beta-hemihydrates appear to differ only in crystal sizes. Alpha types are more prismatic than beta types and when mixed with water, form a much stronger and harder superstructure. The two modifications are defined according to the mode of preparation; the α-form being prepared by wet method (e.g., autoclaving) and the β-form being prepared by dry methods (e.g., calcining) from gypsum (Lewry and Williamson, 1994). The differences in reactivity of the α- and β-forms with water again appeared to be due to their different physical states (Lewry and Williamson, 1994).

On mixing hemihydrate with water, the following reaction occurs:

$$CaSO_4.1/2H_2O + 3/2\ H_2O \rightarrow CaSO_4.2H_2O \qquad (1)$$
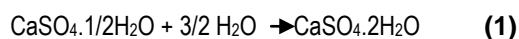
This is the reaction that occurs in the use of POP to manufacture gypsum boards. In the recovery of the powder, the reverse reaction, that is, the

reduction of water of hydration is what is explored.

A considerable amount of waste POP or gypsum board is produced in the pottery, sanitary ware, and construction industries. Conventionally, this waste product has usually been disposed of in landfill sites and the like. This is becoming uneconomical due to the increasing cost of gypsum and particularly, with diminishing productivity of some sources of gypsum, and also the introduction of landfill taxes and the likes. There is also the environmental pollution problem, as construction material wastes cannot be easily compacted and they do not readily decompose (Abdelfatah and Tabsh, 2008).

Waste gypsum building materials are generated in any of three different ways: during the gypsum board manufacturing process, from new construction and from remodeling/demolition. Waste gypsum boards coming from demolition and gypsum board factories represent a serious threat to the environment as they accumulate by thousands to hundreds of thousands of tons in many dumping sites. They retain humidity and thus promote the formation of undesirable mildew.

Degradation of the calcium sulphate contained in the waste gypsum boards under influence of infra-red and ultraviolet radiations causes the generation of H_2S and SO_2 which contaminate the environment. Gypsum board contains calcium sulphate dihydrate, silicon dioxide, cellulosic fibers as well as various metal oxides such as aluminum oxide, calcium oxide, ferric oxide, and magnesium oxide. Calcium sulphate dihydrate might thus constitute a big pollution threat to the environment if it continues to mount in current quantities.

All over the world, governments of each nation have put in place stringent laws that would compel the industrialists to devise methods for recycling of the waste generated from their factories. In Japan, disposal of waste gypsum board discharged from building demolitions has become a serious problem due to a large amount of waste gypsum boards (1.38 x 10^6 tons in 2005) discarded as well as due to shortage of landfill sites (Mihara *et al.*, 2008). Recently, an increase in the recycling of waste gypsum boards, has been observed; however, the amount of gypsum boards recycled still remains relatively low (Mihara *et al.,* 2008). To achieve a

sustainable and environment-friendly disposal, it is necessary to develop new waste gypsum recycling processes (Mihara *et al.,* 2008).

Generally, two approaches are considered for the reutilization of waste gypsum boards: material recycling and chemical recycling (Mihara *et al.*, 2008). Regarding the material recycling, waste gypsum boards are at first subjected to a crushing and board paper separation process and then recycled as plaster board material, cement material, or soil improvement agent. In chemical recycling, reductive decomposition of $CaSO_4$ with a reducing agent is carried out. So far, the investigation on reductive decomposition of $CaSO_4$ with H_2, CO, and C has been mainly undertaken to generate SO_2 for the production of Sulfuric acid as well as to recycle lime (CaO) from waste gypsum (Hull *et al.,* 1957).

In their work, Mihara et al. (2008), following the chemical recycling process, proposed the utilization of gypsum boards for production of CaS, which could be subsequently applied in the sulfuration treatment of metal-containing wastewater. They investigated the reductive decomposition behavior of $CaSO_4$ to achieve a selective generation of CaS from waste gypsum boards. Then the CaS generated from $CaSO_4$ was used as a sulfuration agent in the treatment of a simulated nickel-containing wastewater.

In this work, the regeneration of the plaster powder from the waste gypsum board generated during manufacturing processes and from construction sites, is explored. This is aimed at recycling the powder from the waste boards for use in manufacturing new boards. Hence, the binding properties and the compressive strength of the regenerated powder are key.

The following terms are applied to various categories of materials used:

Stale Raw refers to the virgin POP that had stayed over six months.

Fresh Raw refers to the virgin POP newly-supplied by the manufacturers.

Blend refers to the mixture of wholly recycled powder with virgin POP powder at various proportions.

EXPERIMENTAL METHODS

Waste gypsum board pieces, as well as raw gypsum powder, were obtained from the gyspum board manufacturing company (NGR Investment Limited, Ogun State, Nigeria). The waste pieces were fed into laboratory crusher followed by milling. The metallic impurities were removed using magnetic separator while the fibers were removed using a fine sieve. Desired particle size was obtained using 80-mesh sieve size.

Mole of Water of Crystallization

The water of crystallization present was determined using gravimetric analysis. 10g of the sample powder was placed in the petri-dish and oven-dried for six hours at 180^oC. This enables the determination of mass of anhydrous calcium with which were determined the moles of water given off and that of the bone-dried calcium sulphate. The water of crystallization was determined as the quotient of the moles of water lost over moles of anhydrous $CaSO_4$.

Detail calculation and result are presented in Appendix A.

Calcination

The powder (100% recycled) was calcined at 100^0C for 20 mins using an oven calciner. After calcination, the sample was taken out of the calciner, mixed with water in the ratio 1g sample to 1ml distilled water in a plastic jug with circular cross section without ridges. The round section is necessary to ensure smooth mixing of the blends in the mixer. The mixture was then poured into electric stirrer and stirred at 180rpm for 30 seconds ensuring the stirrer tip is positioned at the center of the jug and at least placed not higher than the middle of the depth of the sample to avoid local setting.

This mixture was molded using the standard 100mm height by 50mm diameter metal mold while noting the setting time of the spill sample using a stopwatch. The experiment was further conducted for the recycle powder at 100^0C for the calcination times of 40mins and 60mins. After each calcination period, above procedure of mixing, stirring and molding were repeated while noting the setting characteristics.

Higher calcination temperatures were explored. The experiment was conducted at 120^0C, 140^0C, 160^0C, 180^0C, and 200^0C for 100% recycle sample using the procedure as above. The samples were removed from the mold after proper setting is ensured and then air-dried.

Compressive strength analyses were conducted on the samples using the California Bearing Ratio (CBR) machine. The procedure is as described below.

The calcination conditions giving highest compressive strength was noted for the production of blends. At this condition, calcined sample was mixed with raw POP and water, stirred and molded. Various proportions of raw used with calcined 100% recycled were: 10% raw, 20% raw, and 30% raw. These samples were also subjected to compressive analyses.

Determination of Compressive Strength

Original Area of the standard mold,

$$A_o = \frac{\pi d^2}{4} \qquad (2)$$

where d is the mold diameter.

Corrected Area, $\quad A_1 = \frac{A_o}{1 - \sum} \qquad (3)$

$\sum$ = unit strain

Compressive Strength= $\dfrac{TotalLoad}{CorrectedArea}$ (4)

Detailed calculations and results are presented in Appendix B.

RESULTS AND DISCUSSION

Water of Crystallization

The moles of water of crystallization were found to be two from the gravimetric analysis. This confirms the waste powder to be the dihydrate, $CaSO_4.2H_2O$ resulting from the mixture of the original POP, $CaSO_4.0.5H_2O$ with water.

Thus, the assumption held that the original hemihydrate ($CaSO_4.0.5H_2O$) had been transformed to dihydrate was justified.

Color of Mold

The raw Plaster of Paris has crystal white color (Ababio, 2005). The recycled powder regained whitish color with rise in calcination temperature as seen in Table 1. The calcination at 100^oC gave brownish-white coloration to the powder when mixed with water. The appearance improved with increase in temperature to 120^oC which gave less-brownish white to the powder-water mixture. At 140^oC, the recycled powder regained the quality white color of the original substance giving white coloration to water-powder mixture. This was sustained at 160^oC, 180^oC, and 200^oC.

Table 1: Observed Colors of the Recycled POP at Different Calcination Temperatures.

Temperature (^oC)	Observed Color
100	Brownish white
120	Less brownish (white)
140	White
160	White
180	White
200	White

The recovery of the whiteness of the recycled powder as the temperature rises is a good indication of process reversal from dihydrate form to the hemi-hydrate form.
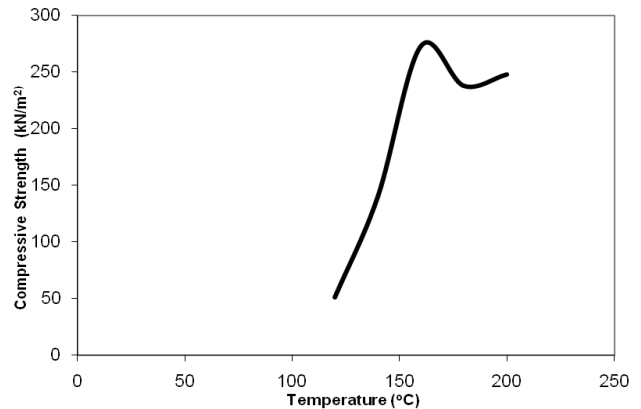
Compressive Strength Variation with Temperature (100% Recycled)

The compressive strength variation with temperature for wholly recycled powder shows the trend depicted in Figure 1. The compressive strength showed considerable improvement in values as temperature rose above 100^oC. The recycled powder treated at 100^oC showed no tendency to set/harden (Table 2), even at infinite time of operation.

At 120^oC, the setting/hardening property was not regained at twenty minutes of calcination, but weak property of hardening was noticed at 40 minutes of exposure to heat. This was further enhanced at the 60mins of calcination. But for

most of the temperature ranges considered, 40 minutes of calcination was most promising. The mold at higher calcination temperatures showed stronger compressive strengths.

Figure 1 reveals the result of the compressive strengths for the products obtained at calcination temperatures of 120^oC, 140^oC, 160^oC, 180^oC, and 200^oC, after 40 minutes of calcination. The weakest of these was at the 120^oC region which has the value of 50.72 kN/m^2. This rose to 140 kN/m^2 at 140^oC and peaked at 160^oC with a value of 273 kN/m^2. A slight decline to 238 kN/m^2 was observed at 180^oC. The 100% recycled powder, at 160^oC, showed a considerable recovery of strength when compared to stale and fresh raw sample molds which gave compressive strengths of 308 KN/m^2 and 409 KN/m^2, respectively (Figure 2).


Figure 1: Compressive Strengths of Recovered Powder at Various Calcination Temperatures (100% Recycle).

Table 2: Setting Time variation with Calcination Temperature

Temperature (^oC)	Setting Time (Mins) (100% Recycle)	Calcination Time (Mins)
100	∞	40
120	1	40
140	2	40
160	6	40
180	8	40
200	11	40

Compressive Strength Variation with Moisture Content (100% recycle @ 160 °C)

Having identified 160°C, from the foregoing results, as the most promising temperature for calcination of the waste plasterboard for strength recovery, investigation of Moisture content effect was carried out. The results revealed increasing strength of the sample molds as the moisture content reduces. At 95% moisture content of the sample, calcined at 160°C for 40 minutes, the compressive strength was 245 KN/m^2. This similar sample calcined at the same temperature but left drying for few days grows in compressive strength to 252 kN/m^2 at 52% moisture content. The trend continues with the strength of 273 kN/m^2 at 20% moisture content while it peaks at 296 at 11% moisture content. (Figure 3).
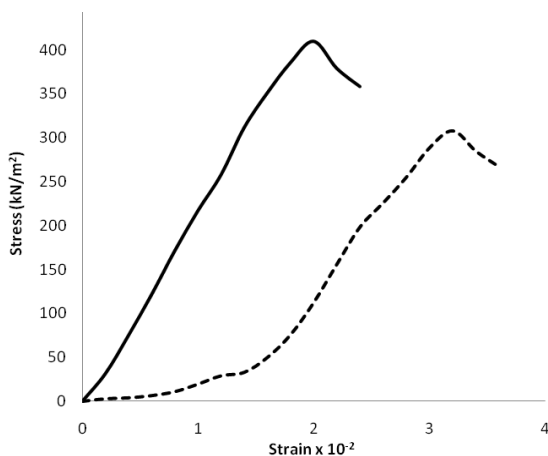

Figure 2: Compressive Strengths of Fresh and Stale Raw.

Compressive Strength Variation with Blend Proportions (Fresh Raw & Recycle at 160 °C)

The possibility of obtaining a product with equivalent compressive strength as the raw POP was explored through blending the recycled powder with the fresh raw POP at proportions of 10%, 20%, and 30% and at a calcination temperature of 160°C (Figure 4).

The results indicate better strength. For the mold of completely-recycled powder (100% recycled), the strength started from a comparatively higher value of 273 kN/m^2. This is followed by a slight decline at 10% blend to 266 KN/M^2. However, the 20% blend gave the remarkable boost to the strength which was 285 kN/m^2 while the 30%

gave 301 kN/m^2 which was almost three-quarters of the strength of the 100% fresh raw POP (421 kN/m^2).
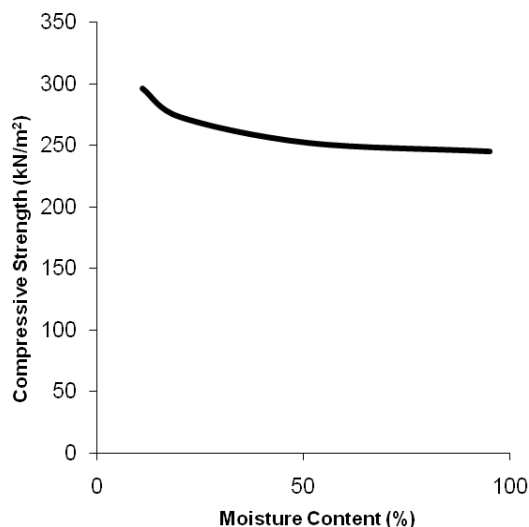

Figure 3: Variation of Compressive Strength with Moisture Content (100% Recycle @ 160°C).

Fashina (2008) explored the direct use of the recovered waste powder without pre-treatment via calcination. He blended the recycled powder directly with raw POP. The 20% blend at this calcination point (160°C) gave strength (285 kN/m^2) more than twice the strength of 70% raw blend (112 kN/m^2) in Fashina's work. The effect further multiplied almost three-fold with 30% raw blend which gave 301 kN/m^2 at this calcination temperature. Figure 4 is the graphical representation of this scenario.

CONCLUSION

Calcination of recovered waste POP has been found to be a satisfactory condition of treatment for the recovery of the compressive strength of the material. Calcination of the recovered POP returns the lost strength to the powder thereby enhancing its reusability. Of all the calcination temperatures investigated, 160°C was optimal. Hence, the re-enhancement of waste plasterboard can be easily achieved with calcination of the waste at this temperature.

The mixture of the raw POP powder with water transformed the hemihydrate to a dihydrate which must be reversed in the resulting waste in order to restore the desired property of strength.
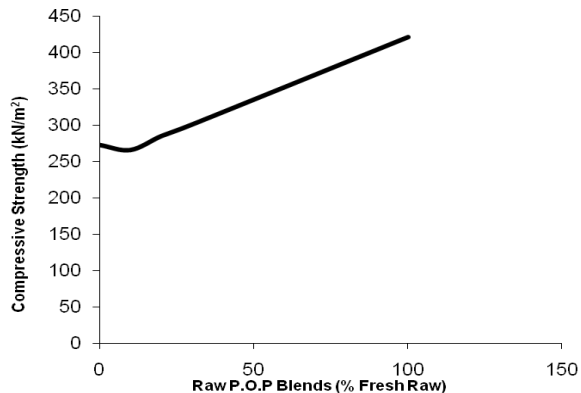
Figure 4: Compressive Strength against Blends (Fresh Raw).

The compressive strength increases with moisture content. So, drying the recycled products under sun for good length of time gives an improved strength to the molds.

Color degradation is another sign of degenerated POP powder as the original and fresh sample retains white appearance. The whitish colour of the original gypsum powder can be easily restored in the waste with calcination above 120^0C.

The raw Plaster of Paris is hygroscopic. It is, thus, necessary to calcine a stale raw Plaster of Paris powder to release the water trapped in its crystal lattices before its eventual use.

APPENDIX A - Determination of Mole of Water of Crystallization

Mass of Dish, Md = 37.15g

Mass of Dish + Recycled powder, Mdp = 47.15g

After heating for six hours at 180^0C

Mass of Dish + Dried Powder, Mdd = 45.36g

Mass of water lost, Mw = 47.15 – 45.36
$$= 1.79g$$

Molar mass of water = 18 g/mol

Mole of water lost, Mow = 1.79/18
$$= 0.099mol$$

Mass of anhydrous $CaSO_4$ = Mdd – Md
$$= 45.36 – 37.15$$
$$= 8.21g$$

Molar mass of $CaSO_4$ = 159.6 g/mol

Mole of anhydrous $CaSO_4$ = 8.21/159.6
$$= 0.051 \text{ mol}$$

To determine x in $CaSO_4 .xH_2O$ (i.e., ratio of mole of water to $CaSO_4$):

x = 0.099/0.051
= 1.94
≈ 2

Therefore, the molecular formula of the compound is:

$CaSO_4. 2H_2O$
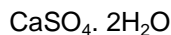
(i.e., the mole of the water of crystallization is 2).

APPENDIX B - Compressive Strength Determination and Strain-Stress Analysis

Parameters Used

Area, Ao = $\dfrac{\Pi d^2}{4}$

Volume = Area x height

Bulk Density, γ_b = $\dfrac{weight}{Volume}$

Water content = $\dfrac{Ww}{Ws}$ x 100%

Ww = water weight (lost in drying)

Ws = dry solid weight

Corrected Area, A1 = $\dfrac{Ao}{1- \sum}$

$\sum$ = unit strain

Stress(Compressive Strength) = Total Load/Corrected Area

Standard Mold Physical Properties

Diameter= 50mm, Height = 100mm

Area, Ao = 1.963×10^{-3}

Volume = 1.963×10^{-4} m^3

Fresh Raw P.O.P (100%)

Weight = 300.64g

Table B1: Compressive Test Results on Fresh Raw P.O.P Mold

Unit Strain($\sum$) ($\Delta L/Lo$) x10^{-2}	Corrected Area, A_1, X 10^{-3} (m^2)	Total Load on Sample Mold (KN)	Mold Stress (KN/M^2)
0	-	0	0
0.2	1.967	62	31.52
0.4	1.971	148	75.09
0.6	1.975	240	121.52
0.8	1.979	339	171.3
1.0	1.983	430	216.84
1.2	1.987	512	257.67
1.4	1.991	620	311.40
1.6	1.995	700	350.88
1.8	1.999	770	385.19
2.0	2.003	820	409.39
2.2	2.007	760	378.67
2.4	2.011	720	358.03

Table B2: Compressive Tests Results on 100% Recycled P.O.P Mold.

Unit Strain($\sum$) ($\Delta L/Lo$)x10^{-2}	Corrected Area, A_1, X 10^{-3} (m^2)	Mold Stress @ 120°C	Mold Stress @ 140°C	Mold Stress @ 160°C	Mold Stress @ 180°C	Mold Stress @ 200°C
0	-	0	0	0	0	0
0.2	1.967	1.02	3.56	19.32	45.75	2.03
0.4	1.971	1.52	6.09	51.04	91.32	16.24
0.6	1.975	2.03	8.10	81.01	121.52	52.66
0.8	1.979	7.07	17.18	116.22	156.64	98.03
1.0	1.983	12.61	28.24	151.29	189.11	139.18
1.2	1.987	18.12	44.29	176.14	216.41	175.14
1.4	1.991	23.10	63.28	195.88	226.02	213.96
1.6	1.995	28.07	83.21	205.51	238.09	238.60
1.8	1.999	34.52	105.05	195.09	230.12	248.12
2.0	2.003	42.44	125.81	192.71	219.67	241.64
2.2	2.007	46.84	139.51	224.22		
2.4	2.011	50.72	115.37	248.63		
2.6	2.015	50.12		272.95		
2.8	2.0195	50.01		260.96		
3.0	2.024	48.91		243.08		
3.2	2.028					
3.4	2.032					
3.6	2.036					

Table B3: Compressive Tests Results on P.O.P Molds of Blends (Fresh Raw) (Calcination @160°C).

Unit Strain(∑) ($\Delta L/L_o$) x10^{-2}	Corrected Area, A_1, X 10-3 (m^2)	Mold Stress @ 10% Raw Blend	Mold Stress @ 20% Raw Blend	Mold Stress @ 30% Raw Blend
0	-	0	0	0
0.2	1.967	28.47	49.82	43.72
0.4	1.971	65.45	90.82	86.25
0.6	1.975	106.33	139.24	131.65
0.8	1.979	146.54	181.91	166.75
1.0	1.983	176.5	216.84	206.76
1.2	1.987	211.37	246.60	241.57
1.4	1.991	215.97	261.18	261.17
1.6	1.995	225.51	269.15	279.33
1.8	1.999	239.24	275.23	290.63
2.0	2.003	250.33	285.11	298.27
2.2	2.007	258.14	262.54	301.16
2.4	2.011	266.05	233.26	293.10
2.6	2.015	240.28	222.19	283.22
2.8	2.0195	211.22		266.63
3.0	2.024			
3.2	2.028			
3.4	2.032			
3.6	2.036			

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Pacific Journal of Science and Technology