Coventry University and
The University of Wisconsin Milwaukee Centre for By-products Utilization,
Second International Conference on Sustainable Construction Materials and Technologies
June 28 - June 30, 2010, Università Politecnica delle Marche, Ancona, Italy.
Main Proceedings ed. J Zachar, P Claisse, T R Naik, E Ganjian. ISBN 978-1-4507-1490-7
http://www.claisse.info/Proceedings.htm

Utilization of Powdered Gypsum-Wallboard in Concrete

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ABSTRACT

Two groups of concrete mixtures, one without sodium sulfate and other with sodium sulfate, as an activator, were made with recycled powdered gypsum-wallboard for this investigation. Group 1 concrete mixtures were made using up to 20% of ASTM Class C fly ash and 20% powdered gypsum while Group 2 contained up to 60% of fly ash and 20% of powdered gypsum by mass. Relevant properties of concrete were evaluated. The study revealed that up to 10% by mass of total cementitious materials could be replaced by powdered gypsum wallboard as a supplementary material without affecting the properties of concrete adversely. Such recycling of the gypsum-wallboard not only reduces the requirement for landfills but also reduces sulfur emissions from decaying gypsum-wallboards in landfills and emission of carbon dioxide and other greenhouse gases by saving the cement quantity in concrete mixtures.

INTRODUCTION

Gypsum-wallboard is one of the most common materials used in the construction of residential as well as official buildings in the United States. It is mainly used as a surface layer on the interior of walls, partitions, and ceilings of the buildings. It provides a surface that could be either easily painted or wall-papered. It further adds to the fire resistance and sound reduction of the buildings. In some cases it may also be used in exterior sheathing applications or in concrete formwork. Gypsum-wallboard is commonly known as drywall, as the need for plaster is eliminated [Merritt and Ricketts 2001]. Over 30 billion square feet of gypsum-wallboard is manufactured each year in the U.S. [Wolkowski 2003]. The primary material used for making wallboard is either natural gypsum or synthetic gypsum. Natural gypsum is mined while synthetic is produced from the flue gas desulfurization process at coal-burning power plants. There are several sources of synthetic gypsum e.g. titanogypsum and others also. The gypsum is mixed into a paste using admixtures, both solid and liquid, spread between two layers of paper, and then cut into specific lengths [Lafarge Group]. The use of the gypsum-wallboard in buildings generates a significant amount of waste during new construction, construction repairs, remodeling, and demolition. Gypsum-wallboard is estimated to be 20% of the solid waste from new residential construction [WI-DNR 2005]. It is estimated that one pound of wallboard waste is generated for each square foot of construction area, or 5 kg/m^2. This generates approximately one ton of waste wallboard in construction of a typical home. Disposal costs from a typical home in Wisconsin cost the homeowner or builder over $700 in for construction wastes. Therefore, assuming that the 20% of the waste is from wallboard, this translates to a disposal cost of about $140 for one ton of waste wallboard resulting from construction of a typical home. There have been challenges associated with the disposal of waste gypsum-wallboard in landfills as there are reports of hydrogen sulfide gas and metal sulfide issues at landfills [Drywallrecycling.org; Krocak et al. 2000]. Citizen lawsuits and health issues have resulted from these emissions [EPA 2004]. Therefore, there is a need to develop environmentally friendly and safe alternative recycling uses for waste gypsum-wallboard that will keep this material out of landfills. In Europe, the most waste gypsum is returned to the plant and re-calcined to make more plasterboard. Only the contaminated material is considered for concrete.

Gypsum (calcium sulfate di-hydrate, $CaSO_4{\cdot}2H_2O$) is an essential ingredient in the manufacture of portland cement. It is used as a set regulator [Wu and Naik 2001, 2002, 2003]. Cement clinkers are interground with approximately 5% of gypsum. Without it, portland cement (specifically, tricalcium aluminate ($3CaO{\cdot}Al_2O_3$, or C_3A) in the cement) will react rapidly with water, and as a result of this, cement will harden too fast and become useless [Kumar and Monteiro 1993]. Thus, a small amount of gypsum is an integral part of portland cement as a set regulator. Powdered gypsum-wallboard may perform s similar function in portland cement. On the other hand, use of a relatively large amount of gypsum may results in false set (stiffness) of fresh concrete mixture due to the rapid formation of large crystals of gypsum [Kumar and Monteiro 1993; Mindness et al. 2002]. Improved reactivity of fly ash and the strength of fly ash concrete due to addition of gypsum were reported [Aimin and Sarkar 1991; Ma et al, 1995; Wu and Naik 2002, 2003]. Prusinski and Carrasquillo 1995 observed that the use of gypsum (above and beyond the amount typically found in portland cement) significantly improved sulfate resistance of concrete made with ASTM Class C fly ash. It was attributed that the gypsum supplied more than enough sulfate to react with all the C_3A and other reactive aluminates in concrete at early ages, so that such aluminates would not be available to render concrete susceptible to cracking due to sulfate attack later. It has also been reported that sodium sulfate (Na_2SO_4) was effective in improving sulfate resistance and early-age strength of concrete containing ASTM Class C fly ash [Freeman and Carrasquillo 1995]. Wu and Naik [2002, 2003] reported that blended cements consisting of portland cement, ASTM Class C fly ash, and spray-dryer ash outperformed plain portland cement in terms of concrete resistance to salt/chloride penetration, sulfate attack, and alkali-silica reaction. A chemical activator was used to increase the early-age reactivity of blended cements [Wu and Naik 2003].

Use of sulfate-bearing materials such as gypsum can increase the formation of needlelike crystals of ettringite (calcium sulfoaluminate hydrate) at early ages and may contribute to the mechanical strength of concrete. If, on the other hand, the alumina-to-sulfate ratio increases later due to depletion of sulfates, ettringite may become unstable and decompose to monosulfate hydrate [Kumar and Monteiro 1993]. In the presence of calcium hydroxide, when sulfate ions get into concrete later, monosulfate hydrate is converted back to ettringite. Since this is an expansive reaction, it can damage hardened concrete. Now it is known and established [Wu and Naik 2002, 2003] that the use of gypsum can stabilize ettringite and that the replacement of cement by fly ash reduces the amounts of aluminate and free calcium hydroxide in concrete. This means that the quantities of susceptible components (monosulfate hydrate and calcium hydroxide) in concrete could be minimized through optimum use of gypsum and fly ash. A chemical activator is helpful in boosting the early-age strength of concrete containing these materials [Wu and Naik 2003]. WRAP [2008] reported a significantly higher rate of carbonation for the concrete specimens containing recycled gypsum. The compressive strength of the concrete used was less than 20 MPa at 28-day and water-to-cementitious material ratio of 0.59. This paper presents results of experimental investigations conducted for the recycling potential of gypsum-wallboard in concrete manufacture.

EXPERIMENTAL INVESTIGATION

Materials

ASTM Type I portland cement and one ASTM Class C fly ash fly were used in this study. The cement and Class C fly ash met the requirements of ASTM standard C 150 and ASTM C 618, respectively. Natural sand and crushed quartzite stone were used as a fine aggregate and coarse aggregate, respectively. The specific gravity, bulk density, SSD water absorption, and void content of sand and aggregates were 2.66, 1550 kg/m^3 (97 lb/ft^3), 0.42%, and 42% and 2.66, 1790 kg/m^3 (112 lb/ft^3), 1.37%, and 33%, respectively.

Type A water reducing admixture (WRA) in accordance with ASTM Standard Specification for Chemical Admixtures for Concrete [ASTM C 494] was used for this study. Table 1 presents the properties and manufacturer's recommended dosage rate of WRA.

Table 1. Properties and Recommended Dosage Rate of WRA

Chemical family name	Specific gravity	Water content (%)	pH	Dosage rate (mL/100 kg of cementitious materials)	Dosage rate (fl oz/100 lb of cementitious materials)
Aqueous solution of lignosulfonate, amine and compound carbohydrates	1.1 - 1.2	~ 50	6.5 - 7.5	190 - 375	3 - 6

Gypsum-wallboard

Gypsum-wallboard was obtained from two locations on the campus of University of Wisconsin-Milwaukee. One source was pieces of drywall from demolition of existing walls, and was designated as "Old". The label on the Old drywall showed that it was "Type SCX" drywall. The other source was cuttings of drywall from new construction, and was designated as "New". It was "Type X" drywall. Both the Old and New gypsum-wallboards contained glass fibers. Type X New gypsum-wallboard appeared to contain more glass fibers than Type SCX Old gypsum-wallboard. Paper covering of the gypsum-wallboard was removed as much as possible, and then the gypsum-wallboard was ground into powder using a laboratory mechanical ball-mill at UWM-CBU. Figure 1 shows powdered gypsum. Due to space limitation, this paper describes the study related to gypsum powder obtained from new gypsum-wallboards only.

Mixture proportions

Table 2 presents the concrete mixture proportions used for this investigation. The mixtures were made in two series. Series1 concrete Mixtures C-2, CN-2, CFN-2, and CFN-3 were made using up to 20% ASTM Class C fly ash and 20% powdered wallboard, with water-reducing admixture, and without sodium sulfate. Series 2 Mixtures Ref-5, CFNS-3, CFNS-4, and CFNS-5 were made using up to 60% ASTM Class C fly ash, 20% powdered wallboard, 2% sodium sulfate, and without water-reducing admixture. Sodium sulfate was added in powder form in the concrete mixture.

Fig. 1. Powdered Gypsum-Wallboard

Table 2. Proportions of Powder Materials Used for Concrete Mixtures

Mixture Designation	C-2	CN-2	CFN-2	CFN-3	C-4	CFNS-3	CFNS-4	CFNS-5
Laboratory mixture designation	Ref-3	New-7	New-8	New-9	Ref-5	New-14	New-15	New-16
Cement (mass % of Cm)	100	90	70	60	100	60	40	20
Fly Ash (mass % of Cm)	0	0	20	20	0	33	50	60
New Gypsum-Wallboard (mass % of Cm)	0	10	10	20	0	7	10	20
Sodium Sulfate (mass % of Cm)	0	0	0	0	0	1	1	2

Cm: Cementitious materials (Cement + Fly Ash + Gypsum-Wallboard).

The mixture proportions and fresh concrete properties of the mixtures are presented in Table 3. In order to evaluate retention of slump of the concrete mixtures, slump was measured twice: (1) immediately after mixing was done; and, (2) 30 minutes later. In general the concrete mixtures retained their workability, although the slump was generally reduced by about 10 to 25 mm.

RESULTS AND DISCUSSIONS

Fresh property tests

Tests for evaluating the fresh properties of the concrete mixtures were conducted according to ASTM standards. Results are presented in Table 3. Addition of powdered gypsum-wallboard in Series 1 concrete mixtures reduced the slump which was maintained with the help of water-reducing admixture. In Series 2 concrete mixtures a reduction in slump value was observed due to increase in powdered gypsum content.

Time of initial setting

The initial setting time of the concrete mixtures are shown in Table 4. It appears from the results that the mixtures containing fly ash and powdered gypsum-wallboard takes more than twice the time to reach the initial setting time compared to the reference concrete Mixtures C-2 and C-4. A larger initial setting time was noticed for concrete having higher percentage of fly ash. It is well known that concrete mixtures containing large amount of fly ash may show delayed setting.

Table 3. Mixture Proportions and Fresh Concrete Properties of Mixtures

Mixture Designation	C-2	CN-2	CFN-2	CFN-3	C-4	CFNS-3	CFNS-4	CFNS-5
Cement (kg/m^3)	362	316	249	212	365	217	144	71
Class C Fly Ash, Weston (kg/m^3)	0	0	71	71	0	119	180	213
Powdered Gypsum-Wallboard, New (kg/m^3)	0	35	35	71	0	25	36	71
Water (kg/m^3)	164	164	170	153	163	154	153	157
Sand, SSD* (kg/m^3)	856	830	840	835	861	854	852	839
Crushed Stone, 19-mm max., SSD (kg/m^3)	1030	999	1010	1010	1030	1030	1020	1010
Sodium Sulfate, Na_2SO_4 (kg/m^3)	0	0	0	0	0	3.6	3.6	7.1
Water-Reducing Admixture (L/m^3)	0	1.03	1.04	1.04	0	0	0	0
Water-Cementitious Ratio, W/Cm	0.45	0.47	0.48	0.43	0.45	0.43	0.42	0.44
Slump (mm)	55	50	40	30	30	40	45	25
Slump, 30 minutes later (mm)	30	40	25	20	40	30	15	15
Air Content (%)	1.8	3.7	2.6	3.2	1.4	2.2	1.5	1.7
Air Temperature (°C)	23	24	23	24	23	23	23	24
Concrete Temperature (°C)	23	23	23	25	24	24	25	25
Density (kg/m^3)	2410	2340	2380	2350	2420	2400	2390	2370

*SSD: Saturated surface-dry.

Table 4. Time of Initial Setting of Concrete Mixtures

Mixture Designation	C-2	CN-2	CFN-2	CFN-3	C-4	CFNS-3	CFNS-4	CFNS-5
Time of Initial Setting (hours)	4.8	7.2	11.4	12.0	4.7	9.8	11.8	10.5

Compressive strength development and durability

The performance of the concrete mixtures was assessed in terms of the rate of development of compressive strength and durability against certain processes (e. g., length change and sulfate resistance). The results are described under subsequent sections.

Compressive strength development

The average compressive strength development at different ages obtained by testing three concrete specimens of the mixtures of Series 1 and Series 2 at each test age is shown in Table 5. Results reported are average of three tests. It can be seen from Table 5 that Mixtures CN-2, CFN-2, and CFN-3 of Series 1 concrete showed a lower compressive strength than Mixture C-2, at all ages, especially at early ages. Mixture CFN-2 showed a compressive strength of 26.5 MPa (3850 psi) at seven days and 41.4 MPa (6000 psi) at 28 days. Mixture CN-2 showed a compressive strength of 28.5 MPa (4140 psi) at 28 days. It is apparent that only Mixture CFN-2 developed a compressive strength compared to reference concrete at 28-day and 91-day. This concrete mixture contained a blend of 20% ASTM Class C fly ash and 10% powdered gypsum by mass of total cementitious materials. Mixture CFN-2 performed even better in comparison with concrete Mixture CN-2 containing 90% cement and 10% powdered gypsum. This implies that the replacements of cement with a blend of ASTM Class C fly ash and powdered gypsum perform better than replacement of cement with only powdered gypsum.

Table 5. Compressive Strength of Concrete Mixtures

Age (days)	C-2	CN-2	CFN-2	CFN-3	C-4	CFNS-3	CFNS-4
1	16.8	11.1	4.2	3.9	15.9	5.8	3.8
3	30.1	19.7	17.4	13.2	30.2	23.7	17.8
7	35.4	23.2	26.5	15.4	34.7	30.1	29.7
28	44.8	28.5	41.4	21.1	40.8	41.5	42.0
91	50.8	41.9	50.1	28.9	51.5	44.3	49.7

It can also be observed from Table 5 that among concrete mixtures of Series 2 concrete, Mixtures CFNS-3 and CFNS-4 developed strength compatible to the reference Mixture C-4 at 28 and 91 days. As early as at seven days, Mixtures CFNS-3 and CFNS-4 showed compressive strength of 30.1 MPa (4370 psi) and 29.7 MPa (4310 psi), respectively. Mixture CFNS-5 performed the worst. The results showed that a blend of powder gypsum (7 to 10% of total cementitious materials) and ASTM Class C fly ash (33 to 50) could be successfully used to make a concrete of 40 MPa (6000 psi) at 28 days.

The cylinders made from Mixture CFNS-5 cracked on their own before reaching the age of seven days. This was attributed to an excessive expansive reaction resulting from use of the particular proportions of cement (20%), fly ash (60%), powdered gypsum-wallboard (20%), and sodium sulfate (2%) in Mixture CFNS-5.

Length change

Test results for length change of the concrete mixtures of Series 1 and Series 2 are shown in Figure 2 and Figure 3, respectively. It is obvious that all the concrete mixtures made with powdered gypsum-wallboard showed higher expansion than the reference concrete Mixtures C-2 and C-4 during immersion in saturated limewater. Mixture CFN-3 containing 20% fly ash and 20% powdered gypsum-wallboard showed a large expansion (0.120%). Specimens made from Mixture CFNS-5 containing 60% fly ash and 20% powdered gypsum-wallboard showed excessive expansion, and they cracked before reaching the age of seven days.

During drying, Mixtures CN-2 and CFN-3, made by using high proportions of powdered gypsum-wallboard to fly ash, shrunk by greater extents than the reference Mixture C-2. At the age of 140 days, the net shrinkage of Mixture CN-2 was 0.035%, which was approximately the same as that of C-2, 0.036%. Mixture CFN-3 showed a net expansion of 0.027% at 140 day. Mixture CFN-2 shrunk by approximately the same amount as Mixture C-2, resulting in a net shrinkage of 0.017% at 140 days.

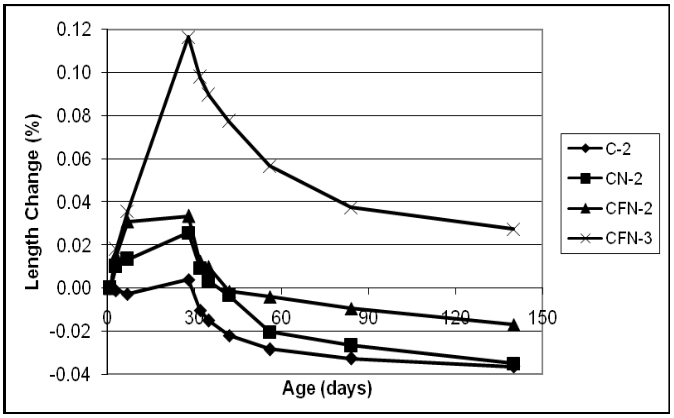

Fig. 2. Length Change of Series 1 Concrete Mixtures

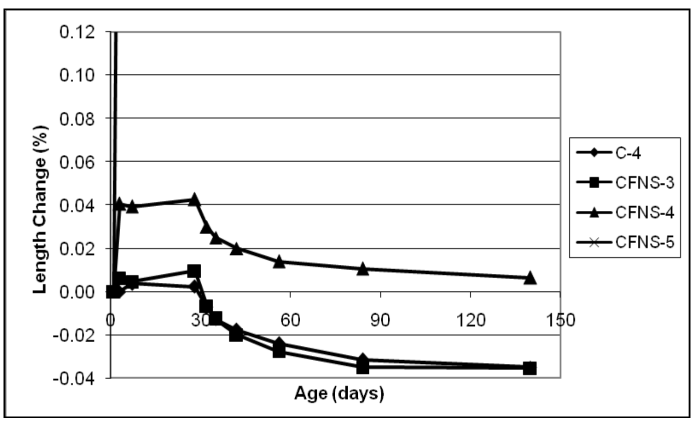

Fig. 3. Length Change of Series 2 Concrete Mixtures

The length change of Mixture CFNS-3 (made with 60% cement, 33% fly ash, and 7% powdered gypsum-wallboard) was approximately the same as that of Mixture Ref-5(OR C-4). Mixture CFNS-4 (made with 40% cement, 50% fly ash, and 10% powdered gypsum wallboard) showed a relatively large expansion (0.043%) during immersion in saturated limewater, and shrunk during drying as much as it had expanded, resulting in very small net expansion of 0.006% at the age of 140 days. This concrete mixture could be used to minimize drying shrinkage cracking of concrete. Such concrete mixture could be used for reducing drying shrinkage cracking, and, therefore, increasing durability, of concrete.

Sulfate resistance

Mortar cubes and bars were made using the same proportions of cement, fly ash, and powder gypsum-wallboard as the final concrete mixtures Ref-5, CFNS-3, and CFNS-4. Mortar mixture was not made using the wallboard powder material for concrete Mixture CFNS-5 because it was anticipated that, similar to the concrete Mixture CFNS-5, such mortar would crack. Table 6 shows the mixture proportions and flow of mortar mixtures.

Table 6. Mixture Proportions and Flow of Mortar Mixtures

Mixture Designation	C-c	C-b	CFNS-1c	CFNS-1b	CFNS-2c	CFNS-2b
Laboratory mixture designation	C-2 cube	C-2 bar	N-3 cube	N-3 bar	N-4 cube	N-4 bar
Cement (mass % of Cm)	100	100	60	60	40	40
Fly Ash (mass % of Cm)	0	0	33	33	50	50
New Gypsum-Wallboard (mass % of Cm)	0	0	7	7	10	10
Sodium Sulfate (mass % of Cm)	0	0	1	1	1	1
Cement (g)	500	740	300	444	200	296
ASTM Class C Fly Ash, (g)	0	0	165	244.2	250	370
Powdered Gypsum-Wallboard, New (g)	0	0	35	51.8	50	74
Sodium Sulfate, Na_2SO_4 (g)	0	0	5	7.4	5	7.6
Water (g)	242	359	216	320.4	200	296.7
Water-Cementitious Ratio, W/Cm	0.48	0.49	0.43	0.43	0.40	0.40
Graded Standard Sand (g)	1375	2035	1375	2035	1375	2035
Flow (mm)	190	…	185	…	191	…

Cm: Cementitious materials (Cement + Fly Ash + Gypsum Wallboard).

Table 7 shows test results for the compressive strength of mortar mixtures. It took approximately 1.5 days for Mixture C-c to attain a compressive strength of 20 MPa (2,900 psi). For Mixture CFNS-1c, it took 4.7 days and for Mixture CFNS-2c, 7 days. Once the mixture attained this strength then the mortar bars are immersed in a 5% sodium sulfate solution for the measurement of length change after specific period to assess its sulfate resistance.

Table 7. Compressive Strength of Mortar (MPa)

Age (days)	C-c	CFNS-1c	CFNS-2c
1	14.8	4.5	1.1
4	31.4	17.4	11.1
5	…	21.2	…
5.125	…	…	16.7
7	…	…	19.7
24	…	…	25.0
28	39.6	31.6	

Note: These results are averages obtained from testing two cubes for each mixture at each test age.

Table 8 shows test results for length change of the mortar bars. A larger expansion implies a lower resistance of mortar mixture to sulfate attack, and a smaller expansion implies a higher resistance to sulfate attack. After 56 days of immersion in sodium sulfate solution, Mixture

C-b (Control) showed an expansion of approximately 0.034%; Mixture CFNS-1c (made with 33% fly ash, 7% powdered gypsum-wallboard, and 1% sodium sulfate) shows an expansion of 0.063%, which was approximately double that of Mixture C-b. Mixture CFNS-2c (made with 50% fly ash, 10% powdered gypsum wallboard, and 1% sodium sulfate) showed an expansion of 0.010%, which is about 1/3 as much, i. e., significantly lower than that of Mixture C-b (Control). This means that Mixture CFNS-2c possesses significantly higher

Table 8. Length Change of Mortar Bars (%)

Age after immersion in 5% sodium sulfate solution (days)	C-b*	CFNS-1b*	CFNS-2b*
7	0.007	0.016	0.006
14	0.013	0.024	0.009
21	0.016	0.028	0.009
28	0.020	0.033	0.009
42	0.027	0.044	0.011
56	0.034	0.063	0.010

* Number of specimens tested: Mixture C-b, five; Mixture N-1-b, six; and, Mixture N-2-b, three. Minimum three replicate test specimens required per ASTM C 1012.

resistance to sulfate attack than the control Mixture C-b. It is also apparent from Table 14 that the expansion of mortar bars made from Mixture CFNS-2c increased rapidly and then stabilized after 14 days of immersion in sodium sulfate solution.

ECONOMICAL AND ENVIRONMENTAL APPRAISAL OF USING POWDERED GYPSUM IN CONCRETE

Environmental factors are moving against portland cement manufacturers due to large amount of CO_2 emissions created by the manufacture of portland cement. On the other hand, maximum use of recycled gypsum obtained from gypsum-wallboard in concrete and concrete products may reduce raw materials such as cement clinker and associated CO_2 emission. It is estimated that over 80,000 tons of gypsum-wallboard is disposed off each year from new construction and demolition activities in the state of Wisconsin alone. For the entire USA, this is equivalent to 4,000,000 tons of gypsum-wallboard thrown away per year. This is a waste of useful resource. If a tipping/disposal fee plus handling and transportation cost of $30 per ton is assumed, the disposal of gypsum-wallboard costs Wisconsin citizens approximately $2.4 million dollars each year.

Based on figures from the National Ready-Mixed Concrete Association, Wisconsin produced approximately 11 million cubic yards (8.4 million m^3) of concrete in 2004. For average cement content of 450 pounds per cubic yard (275 kg/m^3) of concrete makes a consumption of 2.5 million tons of cement in concrete each year in Wisconsin. Based up on the study reported in this paper, powdered gypsum-wallboard can be used in concrete up to 10% of total cementitious materials without adversely effecting concrete properties. If this powdered gypsum was used in 20% of the concrete produced in Wisconsin then 50,000 tons of gypsum-wallboard could be used in concrete. In other words, approximately half of the gypsum wallboard "waste" generated in Wisconsin could be readily recycled in this application alone. This would save Wisconsin $1.5 million dollars each year, in avoided disposal costs, leading to reduce the cost for concrete construction for the citizens of Wisconsin. They would benefit also by reducing needs of landfilling for municipalities and increasing recycling rates of useful materials. This economic impact does not include incalculable dollar-benefits due to avoided possible future environmental impact of sending such large quantities of gypsum wallboard into landfills. Saving portland cement through this new technology would also reduce emissions of carbon dioxide and other GHGs and would yield carbon credits. CO_2 credits typically sell for about $30 (+/- $10) per ton. Therefore, CO_2 credits would be worth $7.5 million each year at $30m per ton of CO2.

CONCLUSIONS

The following general conclusions can be drawn from the study provided in the paper:

- Up to 30% to 60% of cement in concrete mixtures could be successfully replaced with blends of Class C fly ash and powdered gypsum-wallboard.
- Concrete mixtures containing up to 10% powdered gypsum-wallboard by mass of the total cementitious materials showed 28-day compressive strength equivalent to that of the control concrete mixtures (without replacement of cement).
- Use of sodium sulfate as an activator was essential in improving the 1-day and 3-day strength of concrete containing blend of Class C fly ash and gypsum-wallboard.
- A concrete mixture made with a cementitious blend of 40% cement, 50% Class C fly ash, and 10% powdered gypsum-wallboard showed a relatively large expansion (0.043%) during immersion in saturated limewater, and shrunk during drying as much as it had expanded, resulting in very small net expansion at the age of 140 days. This concrete mixture could be used to minimize drying shrinkage cracking and subsequent increase in durability of concrete.
- A mortar mixture made with a cementitious blend of 40% cement, 50% Class C fly ash, and 10% powdered gypsum-wallboard showed much higher resistance to sulfate attack compared with the control mortar (without replacement of cement).
- Use of powdered gypsum-wallboard in concrete causes a reduction in the quantity of cement clinkers required for manufacturing of cement, which would result in reduction of CO_2 emission and earning of carbon credits.

ACKNOWLEDGEMENTS

Support for this research project was provided by UWS-SWRP. Ms. Eileen Norby was the Project Manager for UWS-SWRP. The interest of UWS-SWRP and dedication of Eileen Norby for recycling issues is gratefully acknowledged. The draft of this manuscript was prepared by Dr. Rakesh Kumar, Post-Doctorate Fellow at UWM Center for By-Products Utilization (UWM-CBU). The UWM-CBU was established in 1988 with a generous grant from the Dairyland Power Cooperative, La Crosse, Wisc.; Madison Gas and Electric Company, Madison, Wisc.; National Minerals Corporation, St. Paul, Minn.; Northern States Power Company, Eau Claire, Wisc.; We Energies, Milwaukee, Wisc.; Wisconsin Power and Light Company, Madison, Wisc.; and, Wisconsin Public Service Corporation, Green Bay, Wisc.. Their financial support and additional grant and support from Manitowoc Public Utilities, Manitowoc, Wisc., are gratefully acknowledged.

REFERENCES

ASTM C 33. “Standard Specification for Concrete Aggregates.” *ASTM International, West Conshohocken,* PA, 11 pages.

ASTM C 192 / C 192M. "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory." 8 pages.

ASTM C 150. "Standard Specification for Portland Cement," *ASTM International, West Conshohocken*, PA, 8 pages.

ASTM C 494/C 494M. "Standard Specification for Chemical Admixtures for Concrete." *ASTM International*, West Conshohocken, PA, 10 pages.

ASTM C 618. "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete." *ASTM International*, West Conshohocken, PA, 3 pages.

ASTM C 1012. "Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution."*ASTM International*, West Conshohocken, PA, 3 pages.

Aimin, X., and Sarkar, S. L. (1991). "Microstructural Study of Gypsum Activated Fly Ash Hydration in Cement Paste." *Cement and Concrete Research*, 21(1), 1137-1147.

Drywallrecycling.org < http://www.drywallrecycling.org> (Feb. 10, 2006).

EPA. (2004). Presentation by the U.S. Environmental Protection Agency at the Massachusetts DEP Gypsum Workgroup, March 18.

Freeman, R. B., and Carrasquillo, R. L. (1995). "Production of Sulfate-Resistant Concrete Containing High-Calcium Fly Ash and Sodium Sulfate Admixture." *Proceedings of Fifth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, ACI SP-153, 1(1),153-176.

Krocak, R. F., Meininger, R., and Yost, P. A. (2000). "Chapter 21: Beneficial Reuse of Aggregate Mineral Fines and Scrap New Construction Wallboard." *Land Application of Agricultural, Industrial, and Municipal By-Products (#6), James F. Powers and Warren P. Dick, ed.; SSSA Number 6 in the Soil Science Society of America Book Series*, ISBN 0-89118-834-7, Item Number 60901, 653 pages.

Lafarge Group,< http://www.lafarge.com> (Feb. 10, 2006).

Ma, W., Liu, C., Brown, P. W., and Komarneni, S. (1995). "Pore Structures of Fly Ashes Activated By $Ca(OH)_2$ and $CaSO_4 \cdot 2H_2O$."*Cement and Concrete Research*, 5(2), 417-425.

Mehta, P. K., and Monteiro P. J. M. (1993). "Concrete: Microstructure, Properties, and Materials," 2nd Ed., McGraw-Hill.

Merritt, F. S., and Ricketts, J. T. (2001). "*Building Design and Construction Handbook."* McGraw Hill, 6th Ed., 435-438.

Mindness, S., Young, J. F., and Darwin, D. (2002). "Concrete." 2nd Ed., Prentice Hall.

Prusinski, J. R., and Carrasquillo, R. L. (1995) "Using Medium- to High-Volume Fly Ash Blended Cements to Improve the Sulfate Resistance of High-Lime Fly Ash Concrete." *Proceedings of Fifth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, ACI SP-153, 1(1), 43-65.

WI-DNR (2005). "Substituting Waste Gypsum-Wallboard for Agricultural Gypsum." *Wisconsin Department of Natural Resources, Bureau of Waste Management, DNR Publication WA-607-04 Rev.*

Wolkowski, R. P. (2003). "Using Recycled Wallboard for Crop Production (A3782)." *WasteCap Wisconsin, Inc.*

WRAP (Waste & Resources Action Programme) (2008). "Recycled Gypsum in Concrete Construction Product Applications."<http:\\www.wrap.org.uk/construction> (Aug. 5, 2009).

Wu, Z., and Naik, T. R. (2001). "Use of Clean Coal Ash as Setting Time Regulator in Portland Cement." *Proceedings of the Fifth CANMET/ACI International Conference on Recent Advances in Concrete Technology, Supplementary Papers*, 2001, 83-94.

Wu, Z., and Naik, T. R. (2002). "Properties of Concrete Produced from Multicomponent Blended Cements." *Cement and Concrete Research*, 32(1), 1937-1942.

Wu, Z., and Naik, T. R. (2003). "Chemically Activated Blended Cements." *ACI Materials Journal*, September-October 2003, 434-440.