

# Effect of magnesium oxychloride cement on stabilization/solidification of sewage sludge

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## ABSTRACT

Solidification/stabilization (S/S) is considered to be a well-established disposal technique to reduce sludge handling and disposal obstacles. In this work, the sewage sludge was solidified at variable proportions with magnesium oxychloride cement (denoted as MOC thereafter) as reagent. The mortar prism samples of  $40 \times 40 \times 160$  mm in dimension were prepared and hardened for 24 h at room temperature. Unconfined compressive strength after 10-day curing time, initial and final setting time, X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), and toxicity leachability of the samples, were used to characterize the macroscopic and microscopic effects caused by the solidified products on the MOC hydration process. The results revealed that the magnesium hydration of phase 3, phase 5 and other hydration components in CS developed a crystallizing network in the hydrated solidified products, which not only enhanced the strength of CS but also prevented the precipitation of heavy metal ions from CS.

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## 1. Introduction

Sewage sludge generated with high moisture content or high levels of heavy metals cannot be disposed of directly into the land disposal due to risk of environmental contamination. Solidification/stabilization (S/S) is known as a pretreatment process of sewage sludge to reduce sludge handling or disposal problems by their encapsulation into a solid matrix as physically and/or chemically stable as possible [1,2]. Currently, various binders or additive agents, such as Portland cement, lime, emulsified asphalt or other additives, have been used [3–5]. But cementitious solidification (Alkaline matrices of cement or lime) is always recognized as best available technology [6], because they are inexpensive, readily incorporate wet wastes and their alkalinity reduces the solubility of many inorganic toxic or hazardous metals.

In this paper, magnesium oxychloride cement (MOC) was investigated as an alternative cementitious media in the S/S process of sewage sludge. MOC, also known as Sorel cement, is a combination of magnesia ( $\text{MgO}$ ) and magnesium chloride ( $\text{MgCl}_2$ ). Compare with Portland cement, MOC is a type of non-hydraulic and rapid hardening media [7,8]. When it is mixed with sewage sludge, powdered  $\text{MgO}$  and  $\text{MgCl}_2$  may react on water contained in the sludge.

$\text{MgO-MgCl}_2\text{-H}_2\text{O}$  ternary system will be formed in the hydration process [9]. Two main reaction phases,  $3 \text{Mg}(\text{OH})_2 \cdot \text{MgCl}_2 \cdot 8\text{H}_2\text{O}$  (phase 3) and  $5 \text{Mg}(\text{OH})_2 \cdot \text{MgCl}_2 \cdot 8\text{H}_2\text{O}$  (phase 5), particularly exist as reinforced components in the ternary system at ambient temperature [10]. Shape of phase 3 and phase 5 may be observed as needlelike or long-tree-like crystal at SEM images [11]. The crystals are aggregated and connected each other at crystallization point even like net structure on condition that hydration would be reacted completely.

The present study aims at developing an appropriate S/S technology for the disposal of sewage sludge with MOC. The influences of the ratios of  $\text{MgO/MgCl}_2$  and MOC/sludge, strength development, XRD, SEM and leaching test on the S/S process were analyzed separately and the S/S mechanism of MOC was discussed.

## 2. Experimental

### 2.1. Materials

#### 2.1.1. Type of sludge

The sewage sludge was taken from Bailonggang Sewage Treatment Plant (BSTP) in Shanghai. BSTP is one of the largest sewage treatment plants in China in terms of processing capacity, approximately  $2,300,000 \text{ m}^3/\text{day}$  of municipal wastewater are subjected to primary treatment. Poly aluminum chloride (PAC) was adopted as precipitator, and polyacrylamide (PAM) was used as coagulant aids in enhanced primary treatment procedure in BSTP. About 2040 tonnes/day of dewatered sewage sludge were produced. It was brown in color due to presence of irons and was called as chemical sludge (CS).

Chemical sludge was characterized using the standard methods of analysis [12]. Total organic carbon (TOC) was measured by titrimetric method [13] and the con-

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centrations of heavy metals were obtained using inductively coupled plasma atomic emission spectrometry (ICP-AES) analysis. The results are shown in Tables 1 and 2.

### 2.1.2. Binders

Magnesia (MgO), powder type and commercial grade, with a purity of 98%, bulk density of 0.35 g/cm<sup>3</sup>, Sieve Residue (200 mesh) of 0.05, and Ca < 0.05%, Fe < 0.005%, Pb < 0.004%, and Magnesium chloride (MgCl<sub>2</sub>) of hexahydrate crystal, with high water adsorption and deliquescent effect even in moist air, were used as binders for the sludge.

### 2.2. Test procedures

All the samples were prepared by mixing CS and MOC. Components of MOC were MgO and MgCl<sub>2</sub> in different molar ratios ranging from 1:1 to 5:1, with a mass ratio of MOC/CS between 100:1 and 100:20 as given in Table 3. As shown in Table 1, moisture content of CS was higher than 80%, hence addition of water was not required and the equal workability of all the mixtures could be obtained.

MgCl<sub>2</sub> was added in the surface of CS with centrifugal swinging for 5 min until it absorbed water from sludge and deliquescence. Then the centrifugal swing machine was stopped and MgO was added. MOC, including MgCl<sub>2</sub> and MgO, dispersed in CS with a mixer at higher speed (800 r/min) for 3 min. The mixing procedure was the same for all mortars and twelve samples were made at same ratio. The mixtures were solidified in steel molds with a size of 40 × 40 × 160 mm for 24 h, and the resultant products were extruded and cured in airtight condition of 20 °C ± 0.5 °C for 10 days.

**Table 1**  
Characteristics of chemical sludge used.

Sludge property	Chemical sludge (cs)
Moisture content (%)	85.4
Total organic carbon (%)	23
pH	6.65
Coefficient of permeability (cm/s)	$1.2 \times 10^{-8}$
Unconfined compressive strength (kg/cm <sup>2</sup> )	0.085
Heavy metals (mg/kg) <sup>a</sup>	
Cu	3500
Zn	5984
Pb	112
Cd	8.57
Cr	670
Ni	34.8
As	224

<sup>a</sup> Concentration of heavy metals (mg/kg dry sludge).

**Table 2**  
Chemical analysis of chemical sludge used.

Parameters	Values (%) <sup>a</sup>
Silica (SiO <sub>2</sub> )	24.52
Lime (CaO)	16.33
Alumina (Al <sub>2</sub> O <sub>3</sub> )	35.65
Magnesia (MgO)	2.84
Iron oxide (Fe <sub>2</sub> O <sub>3</sub> )	16.19
Loss on ignition <sup>b</sup>	9.67

<sup>a</sup> Dry sludge ash.

<sup>b</sup> Loss on ignition at 1100 °C.

**Table 3**  
The study matrix of CS and MOC with different ratios.

Molar ratio of MgO/MgCl <sub>2</sub>	Mass ratio of MOC/CS				
	CS1 = 1:100	CS2 = 3:100	CS3 = 5:100	CS4 = 10:100	CS5 = 20:100
M1 = 1:1	✓	✓	✓	✓	✓
M2 = 2:1	✓	✓	✓	✓	✓
M3 = 3:1	✓	✓	✓	✓	✓
M4 = 4:1	✓	✓	✓	✓	✓
M5 = 5:1	✓	✓	✓	✓	✓

✓ – Components and ratio of mixtures.

### 2.3. Samples analysis

#### 2.3.1. Compressive strength analysis

Unconfined compression strength (UCS) was tested using the unconfined compression machine with a maximum load of 5 kN. The cubes were tested for their 1-day, 3-day, 7-day, 10-day compression strength at a loading rate of 1.52 mm/min. Three samples for each mix series were tested and average value was obtained.

#### 2.3.2. Setting time analysis

The setting time of the mixtures was determined by a Vicat apparatus at room temperature [14]. The initial setting time was defined as when a Vicat needle 1 mm in diameter would penetrate the sample to a point 5 ± 1 mm from the bottom of the mould. The final setting time was defined as when a 5-mm cap ring would leave no visible mark when placed on the surface of the samples.

#### 2.3.3. XRD analysis

The mineralogical composition was determined by X-ray diffraction (XRD). For XRD pretreatment, oven-dried sludge was ground by mortar pastel and passed through 200-mesh (74 μm) sieve. Then the XRD analysis was carried out by X-ray diffractometer with Cu Kα radiation, 30 kV of acceleration voltage condition and 2θ scanning, ranging from 0° to 70°.

#### 2.3.4. SEM analysis

Scanning Electron Microscopy (SEM) analysis was performed on the dried samples of before and after solidification with MOC. The samples were gilt with Au and SEM was operated at 15 kV of acceleration voltage.

#### 2.3.5. Leaching tests

Leachability of solidified CS was evaluated using standard leaching method: the Toxicity Characteristics Leaching Procedure (TCLP, EPASW-846) in USA. The leaching solution was prepared at a liquid–solid ratio of 5:1 and stirred at 110 rpm for 24 h. Aqueous solution is acetic acid with pH value of 2.88 ± 0.05. The heavy metals leaching from the samples were analyzed by ICP-AES.

## 3. Results

### 3.1. Effect on unconfined compressive strength

Unconfined compressive strength (UCS) is one of the important parameters for solidified effect. As shown in Fig. 1, with increase of the proportion of MOC, the sludge strength increases concomitantly. At a fixed molar ratio of MgO/MgCl<sub>2</sub>, e.g. 3:1 (M3), the corresponding UCS of CS1, CS2, CS3, CS4, CS5 series (mass ratios of MOC/CS are 1/100, 3/100, 5/100, 10/100, 20/100) is found to be 1.36 kg/cm<sup>2</sup>, 8.96 kg/cm<sup>2</sup>, 20.17 kg/cm<sup>2</sup>, 70.67 kg/cm<sup>2</sup>, 85.14 kg/cm<sup>2</sup>, respectively, meaning that the strength of CS increases significantly with the addition of MOC. The same trends also occur in other molar ratios of MgO/MgCl<sub>2</sub>. It is also found that the minimum UCS is 0.75 kg/cm<sup>2</sup> of M1CS1. Except it, UCS of other solidified products are higher than 5.99 kg/cm<sup>2</sup>, meeting the EPA limit of a solidified material with strength of 50 psi (pounds per square inch) = 3.44 kg/cm<sup>2</sup> (US EPA OWSE Directive, No. 9437.00-2A).

UCS of CS3 series were detected in 1-day, 3-day, 7-days and 10-day. Fig. 2 shows that molar ratio of MgO/MgCl<sub>2</sub> can affect the strength of solidified CS. Because of the higher strength of M3 (MgO/MgCl<sub>2</sub> = 3:1) than others, the optimal molar ratio of MgO/MgCl<sub>2</sub> in CS3 series can be obtained. It is also found that the strength development curves are ascending but the rising trend

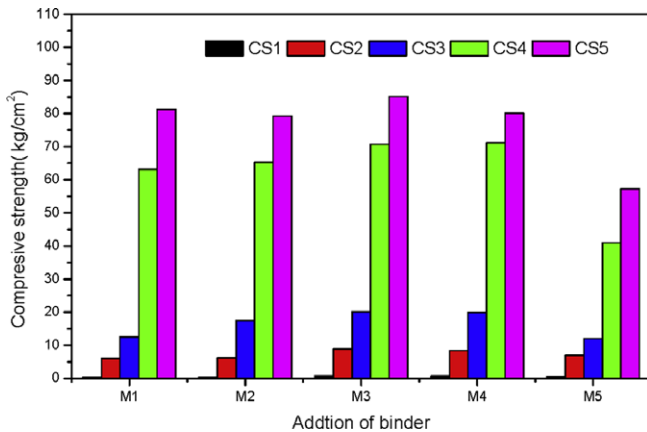


Fig. 1. Compressive strengths of different mixtures after air curing of 10 days.

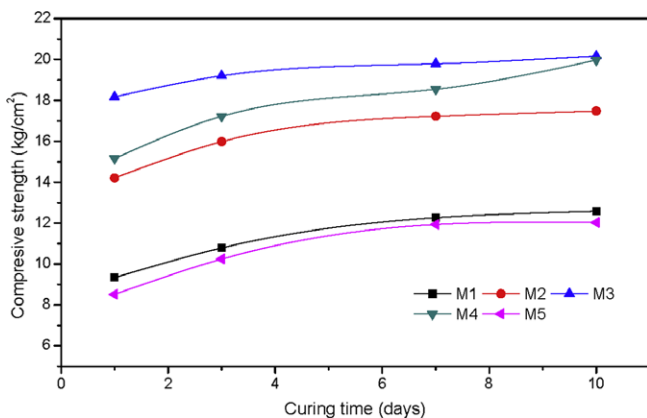


Fig. 2. Strength developments of the samples of MOC/CS3.

is flat, which may be contributed to the reinforced reaction of mixture occurred and finished in steel molds in the initial period. As a result, the later strength in the curing time increased slowly.

### 3.2. Effect on setting time

Setting time in the hydration crystal process of MOC is the vital step for the fabrication of a dense and chemically stable material in the MOC–CS mixtures [15]. Table 4 shows that the initial setting time may be determined by the ratio of MOC/CS and the initial and the final setting time are shortened with raising the proportion of MOC. The longest final setting time was 17.6 h for M1CS1, while the shortest final setting time was 11.6 h under the case of M3CS3. Especially in CS5 series, the initial setting times are less than 1 h and the final time is as short as 11.8 h. Moreover, the variation of

Table 4  
Results of speed setting time.

Samples	Initial setting time (h)	Final setting time (h)	Moisture after 10 days (%)
M1CS2	2.1 ± 1	17.6 ± 0	64.90
M3CS2	2.4 ± 0	17.0 ± 0	64.38
M3CS3	1.0 ± 0.5	11.6 ± 0	65.53
M5CS3	1.2 ± 0	12.7 ± 0	62.75
M3CS4	1.1 ± 0	11.7 ± 0	55.20
M4CS4	1.5 ± 0	12.3 ± 0	53.17
M3CS5	0.8 ± 0	13.4 ± 1	42.33
M5CS5	0.9 ± 0	11.8 ± 0	45.19

water contents in the solidified products ascribes to the increasing amount of MOC. With increasing amount of the binder, the water contents in the products are lower than unsolidified CS, the minimal value is 42.33% for M3CS5. These results confirms that the hydration reaction of MOC can occur under the condition of less addition of MOC, meaning that the dilution of MOC in CS had not adverse influences on the solidification of MOC, and that the water contents of CS apparently decreased in the solidified process.

### 3.3. X-ray diffraction (XRD) analysis

XRD analysis (Fig. 3) was conducted for samples with fixed molar ratio of M3 ( $\text{MgO}/\text{MgCl}_2 = 3:1$ ), which was the optimal molar ratio of MOC and represented a good solidified products. In XRD diffractogram, several typical hydration products were identified, such as phase 3 ( $3 \text{Mg}(\text{OH})_2 \cdot \text{MgCl}_2 \cdot 8\text{H}_2\text{O}$ ) and phase 5 ( $5 \text{Mg}(\text{OH})_2 \cdot \text{MgCl}_2 \cdot 8\text{H}_2\text{O}$ ) and  $\text{Mg}(\text{OH})_2$ . For the reason of the dilution effect of MOC in CS, the gelling reaction is an incomplete reaction and unreacted product of  $\text{Mg}(\text{OH})_2$  is still existed. Some of  $\text{Mg}(\text{OH})_2$  reacted with  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  or  $\text{MgO}$  in CS and pozzolanic effect occurs in the solidified process [16]. As a result, stable crystalline phases of Mg–Si–Al are generally formed, such as Musicovite magnesian 1 M ( $\text{KMgAlSi}_4\text{O}_{10}(\text{OH})_2$ ), Osumilite-(Mg) ( $\text{KMg}_2\text{Al}_3(\text{Si}_{10}\text{Al}_2)_4\text{H}_2\text{O}$ ), Magnesium Aluminum Silicate Hydrate ( $5\text{MgOAl}_2\text{O}_3 \cdot 3\text{SiO}_2 \cdot 4\text{H}_2\text{O}$ ). It can be seen that phase 3 and phase 5 are the main reinforced compounds in CS.

### 3.4. Scanning electron microscopy (SEM) analysis

SEM observations of the samples before and after solidification are shown in Fig. 4. The Platy construct of unsolidified CS is disordered and incompact in Fig. 4a. Fig. 4b shows the typical MOC–CS structure, with the needle-like crystals and honeycomb-like hydrated microstructures on the surface and interior of the solidified CS. In particular, besides the ternary system  $\text{MgO}-\text{MgCl}_2-\text{H}_2\text{O}$  in the MOC, Mg–Si–Al flaky hydration often is contained in the micro-pore space of CS [17]. The crystals are aggregated and connected each other, which distributed in CS and formed a homogeneous network. Under the co-action of  $\text{MgO}-\text{MgCl}_2-\text{H}_2\text{O}$  and Mg–Si–Al gel, the high mechanical strength of CS can be obtained.

### 3.5. Leaching tests

The Leaching tests were performed for determining leachability of copper, zinc, nickel, chromium and arsenic, respectively, in the solidified products. The test samples included CS2, CS3, CS4 and CS5 series. Fig. 5 shows the variation of final leaching concentrations with successive extractions, the data are lower than the detection limit (Table 5) in China and US EPA. In all cases, the different percent retention of heavy metal molecules makes the extraction concentration decreased with the addition of MOC. This fact is corroborated when using a greater amount of MOC, e.g.  $\text{MOC}/\text{CS} = 20:100$ ,  $\text{MgO}/\text{MgCl}_2 = 5/1$ . The obtained leaching concentrations of copper, zinc, nickel, chromium and arsenic are found to be 0.21 mg/L, 0.12 mg/L, 0.03 mg/L, 0.05 mg/L, 0.1 mg/L, with 22.3%, 22.2%, 37.5%, 17.2%, 15.9% of leaching concentrations of M1CS2, respectively. As far as the heavy metal retention was concerned, it can be concluded that the greater amount of the MOC added, the greater the percentage of heavy metal retention in the mixed ratio range of  $\text{MOC}/\text{CS}$  of 3:100–20:100 obtained.

## 4. Discussion

The water content of CS is still more than 85% even after thickening and mechanical dewatering. It is quite difficult to dewater

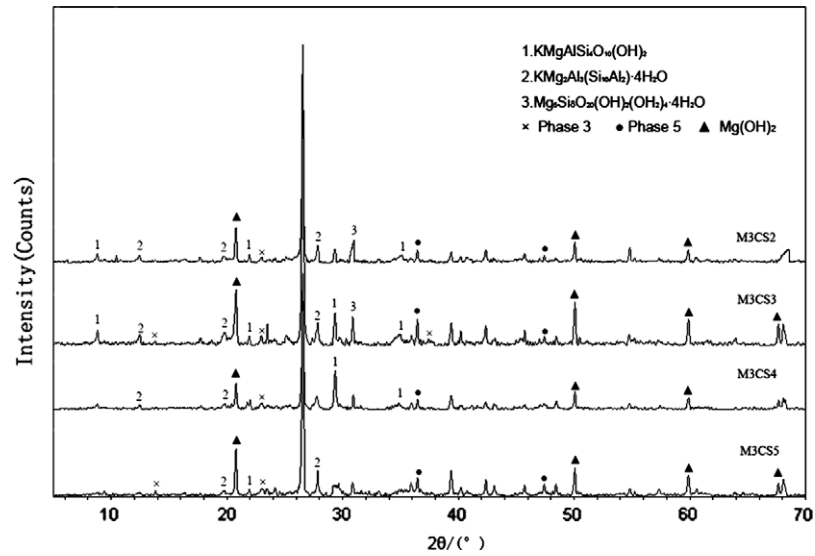


Fig. 3. X-ray diffraction samples.

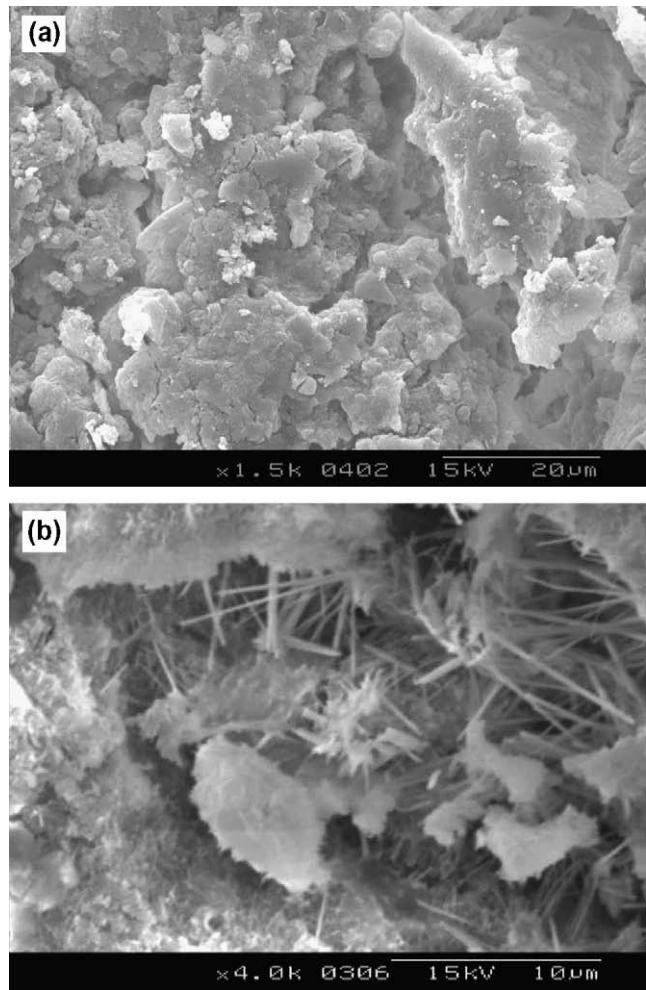


Fig. 4. SEM photographs of MOC/CS: (a) unsolidified CS and (b) solidified CS.

further through dewatering devices.  $MgCl_2$ , which has extremely high water adsorption capacity, is known as strong electrolyte and recommended for dissolving selectively heavy metals in sediment [18]. Under the action of  $MgCl_2$ , partial adsorbed water is re-

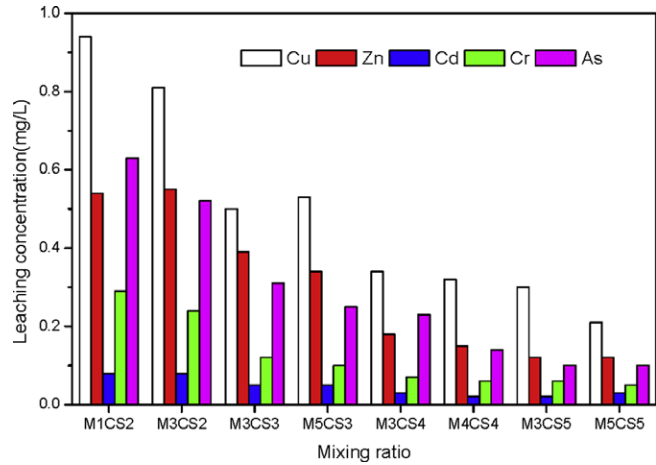


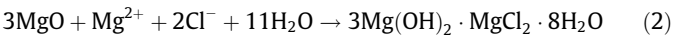
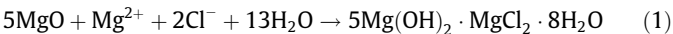
Fig. 5. Heavy metal retention percentage for 10-day-curing samples.

Table 5  
Toxicity characteristic criteria in China and US EPA (mg/L).

Criteria	Cu	Zn	Cd	Cr	As
IEPT	50	50	0.3	10	1.5
EPA TCLP	–	–	1.0	5.0	5.0

leased from CS (Fig. 6).  $MgCl_2$  dissolves in water to form magnesium chloride solution. The dehydration efficiency of  $MgCl_2$  in 100 g CS is 1.55 mL/g, as calculated by the slope of a straight line in Fig. 7.

When MgO is mixed with  $MgCl_2$  solutions in CS and dissolves in it, the MOC gel paste is produced [19] and cement formulations are developed using optimal molar ratio of MgO with  $MgCl_2$  ( $MgO/MgCl_2 = 3:1$ ). In the course of hydration reaction, one part of water in CS evaporated with the hydration heat, and the others enter the hydration products, thus the water content in the products is decreased. These hydrations are generated in the ternary gelatinization system of  $MgO-MgCl_2-H_2O$  as below [20].





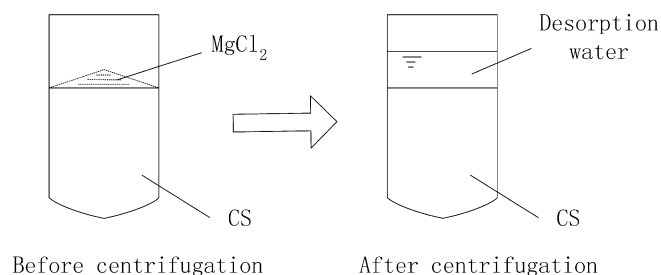


Fig. 6. Method of  $\text{MgCl}_2$  dewatering.

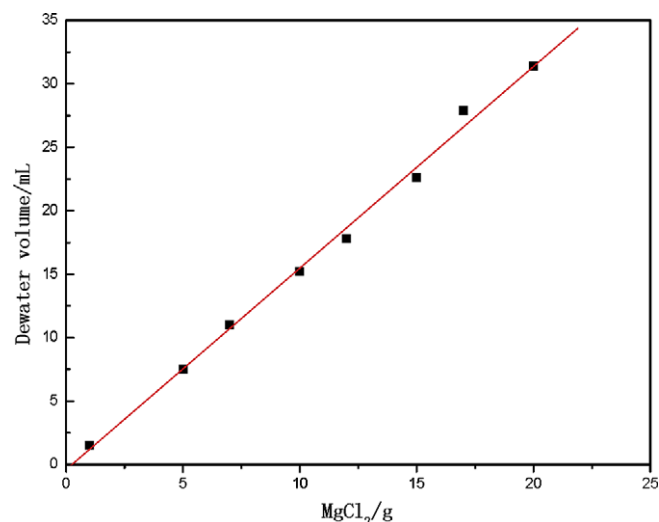


Fig. 7. Relation of dewatering efficiency and  $\text{MgCl}_2$  addition.

$\text{MgO}$  has minimal environmental impact and high alkalinity, reaching a maximum pH of 10, which helps to neutralize acids and precipitate metals. Metals and lower oxidation states of metalloids in sludge are pH dependent, and the solubility of most of metal and metalloid (hydr)oxides such as copper, zinc, nickel, chromium and arsenic is minimal within pH range 9–11 [21]. Addition of  $\text{MgO}$  makes pH of CS close to 9.2 which is controlled by the solubility of the magnesium hydroxide. The concentration of most of the measured heavy metals decreases as a function of percentage of the  $\text{MgO}$  added to stabilize CS.

Otherwise, when MOC is dispersed in CS, the main components,  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  or  $\text{MgO}$  contained in CS can therefore form  $\text{Mg-Si-Al}$  ( $\text{MgO-SiO}_2\text{-Al}_2\text{O}_3\text{-nH}_2\text{O}$ ) hydration with unreacted  $\text{Mg(OH)}_2$ . After a period of curing time, the hydrations of phase 3, phase 5 and other hydration components in CS develop a crystallizing network, which has been observed as by the microstructural study. The crystallizing network not only enhances the strength of CS but also prevents precipitation of heavy metal ions from CS.

## 5. Conclusions

The utilization of MOC as a new type of agent was developed and tested for S/S of CS. The formulation of MOC proved effective for the optimal ratio of compositions ( $\text{MgO/MgCl}_2 = 3:1$ ) that mixed with CS. MOC additives in appropriately mixing proportions

(lowest added ratio is 3:100) might enhance the strength of CS in a short time.

According to the results obtained in this work, the S/S process is a hydrated process of MOC in CS. Firstly,  $\text{MgCl}_2$  absorbed water from sludge and deliquescence, and then  $\text{MgO}$  dissolves in magnesium chloride solution and forms gel paste of MOC. Secondly, the hydration products developing magnesium network in curing time. Just like microstructural analyses in XRD and SEM. It means that effect of MOC on S/S process changes the geotechnical characteristics of CS and enhances the solidifying reaction of the sludge.

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## References

- [1] Malliou O, Katsioti M, Georgiadis A, Katsiri A. Properties of stabilized/solidified admixtures of cement and sewage sludge. *Cem Concr Compos* 2007;29(1):55–61.
- [2] Walter I, Martinez F, Cala V. Heavy metal speciation and phytotoxic effects of three representative sewage sludge for agricultural uses. *Environ Pollut* 2006;139(3):507–14.
- [3] Minocha AK, Jain Neeraj, Verma CL. Effect of inorganic materials on the solidification of heavy metal sludge. *Cem Concr Res* 2003;33(10):1695–701.
- [4] Valls S, Vaázquez E. Stabilisation and solidification of sewage sludges with Portland cement. *Cem Concr Res* 2000;30(10):1671–8.
- [5] Lin KL, Chiang KY, Lin CY. Hydration characteristics of waste sludge ash that is reused in eco-clinkers. *Cem Concr Res* 2005;35(6):1074–81.
- [6] Sarvinder Singh T, Pant KK. Solidification/stabilization of arsenic containing solid wastes using Portland cement, fly ash and polymeric materials. *J Hazard Mater* 2006;131(1):29–36.
- [7] Maravelaki KP, Moraitou G. Sorel's cement mortars: decay susceptibility and effect on Pentelic marble. *Cem Concr Res* 1999;29(12):1929–35.
- [8] Zongjin L, Chau CK. Influence of molar ratios on properties of magnesium oxychloride cement. *Cem Concr Res* 2007;37(6):866–70.
- [9] Guozhong L, Yanzhen Y, Jianquan L, et al. Experimental study on urban refuse/magnesium oxychloride cement compound floor tile. *Cem Concr Res* 2003;33(10):1663–8.
- [10] Beaudoin JJ, Ramachandran VS. Strength development in magnesium oxychloride and other cements. *Cem Concr Res* 1975;5(6):617–30.
- [11] Dehua D, Chuanmei Z. The formation mechanism of the hydrate phases in magnesium oxychloride cement. *Cem Concr Res* 1999;29(9):1365–71.
- [12] China MC. Determination method for municipal sludge in wastewater treatment plant, C/J/T 221-2005. Ministry of construction of the People's Republic of China, Beijing; 2005.
- [13] Adams VD. Water and wastewater examination manual. Michigan: Lewis Publisher; 1990.
- [14] AQSIQ China. Test methods for water requirement of normal consistency, setting time and soundness of the Portland cements, GB/T1346-2001. General administration of quality supervision, inspection and quarantine of the People's Republic of China, Beijing; 2001.
- [15] Hall DA, Stevens R, El-Jazairi B. The effect of retarders on the microstructure and mechanical properties of magnesia-phosphate cement mortar. *Cem Concr Res* 2001;31(3):455–65.
- [16] Zhihong L, Mancheng H, Shiyang G. Phase Equilibrium of  $2\text{MgO}\cdot 2\text{B}_2\text{O}_3\cdot \text{MgCl}_2\cdot 14\text{H}_2\text{O-MgCl}_2\text{-H}_2\text{O}$  system at 30 °C. *Acta Phys Chim Sin* 2002;18(12):1116–9.
- [17] Soudee E, Pera J. Influence of magnesia surface on the setting time of magnesia-phosphate cement. *Cem Concr Res* 2002;32(1):153–7.
- [18] Tessier A, Campbell PGC, Bisson M. Sequential extraction procedure for the speciation of particulate trace metals. *Anal Chem* 1979;51(7):844–51.
- [19] Dehua D. The mechanism for soluble phosphates to improve the water resistance of magnesium oxychloride cement. *Cem Concr Res* 2003;33(9):1311–7.
- [20] Soudee E, Pera J. Mechanism of setting reaction in magnesia-phosphate cements. *Cem Concr Res* 2000;30(2):315–21.
- [21] García MA, Chimenos JM, Fernandez AI. Low-grade  $\text{MgO}$  used to stabilize heavy metals in highly contaminated soils. *Chemosphere* 2004;56(5):481–91.