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著者	Jing Z., Jin F., Yamasaki N., Ishida E.H.
journal or publication title	AIP Conference Proceeding The 4th International workshop on Water Dynamics
volume	898
page range	197-200
year	2007
URL	<a href="http://hdl.handle.net/10097/51651">http://hdl.handle.net/10097/51651</a>

doi: 10.1063/1.2721280

# The Potential Utilization of Sediment of River in Hydrothermal Solidification Process

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**Abstract.** Solidification of sediment of river has been carried out using a hydrothermal processing method, in which the sediment was first compacted in a mold at 20 MPa, and then hydrothermally cured in an autoclave under saturated steam pressure at 200 °C for 12 hrs. The riverbed sediment could be solidified hydrothermally with tobermorite formation, and the addition of slaked lime was favorable to tobermorite formation. The strength development of the solidified specimen depended on amount of tobermorite formed, and the more the tobermorite, the higher the strength. At addition of slaked lime 20-40 mass%, the flexural strength was about 23 MPa, which could be used as construction materials. As such, the hydrothermal processing method may have a high potential of utilization of riverbed sediments as construction materials.

**Keywords:** Sediment of river, Hydrothermal solidification processing, Tobermorite

**PACS:** 91.40.Ge

## INTRODUCTION

The lower Yellow River, China, has a long history of heavy siltation, which suggests that the riverbed was raised by 15-20 m in about 600 years (2.5-4.3 m from 1950 to 1997). The floodlands between the dikes of the current lower Yellow River are 9-15 m higher than the surrounding floodplain because of continuous siltation [1], which has caused heavy losses for people there. The rate of sedimentation in the lower Yellow River was about  $0.2 \times 10^9$  t/year over the period from 1950 to 1985 [1].

For most of the tributaries of the Yellow River, the siltation is the same as that in Yellow River. Now, the Chinese government is managing to harness these rivers and to use their sediments.

A hydrothermal processing method has long been applied to the field of building materials manufacture [2,3], and recently it has also been used to other fields, such as inorganic wastes solidification [4,5]. The solidified body in those studies was shown to possess a reasonable strength, and therefore the hydrothermal solidification technology may have such a potential for the hydrothermal solidification of sediment. The hydrothermal technology has capability of utilizing sediments on massive scale by lower energy consumption due to the lower hydrothermal autoclaving temperature. Ishida [6] reported how the energy required for hydrothermal solidification of earth ceramics is only 1/6 that of energy needed for fired ceramic tiles.

The sediment of the Yellow River and most of their tributaries are sandy silt that can not be used for construction industry as aggregates directly, which is considered as a natural waste now. To the best of our knowledge, there seems to be few published works dealing with utilization of riverbed sediments.

The objective of this study is to investigate potential utilization of sediment of river in hydrothermal solidification process. The results are expected to provide useful information on utilization of the sediments, which should be useful in the use of the materials as pavement materials (tiles and blocks), river and ocean embankment materials, and similar applications.

## EXPERIMENTAL

Sediment of river was obtained from the Weihe River, China, which is the largest tributary of the Yellow River. The sediment in this area comprises two parts, i.e., the upper part consists mainly of silt (sandy loess) with thickness of 0.2 m; and the lower part consists mainly of sand (silty sand) with thickness of 2-3 m. The sediment was used for the experiment in this study without grinding. The particle size distributions as determined by laser diffraction technology (X100, Microtrac), and chemical compositions by x-ray fluorescence (XRF; RIX3100, Rigaku) of the upper silt are shown in Fig. 1 and Table 1, respectively. The silt mixed with slaked lime at different mixing ratio was used as starting materials. The starting material (10 g) was first mixed manually

in a mortar with 15 mass% distilled water (1.5 ml), and then the mixture was compacted by compaction pressure of 20 MPa in a rectangular-shaped mould (15 mm length x 40 mm width x 45 mm height). The demoulded specimens were subsequently autoclaved under the saturated steam pressure (1.56 MPa) at 200 °C for 12 h. The hydrothermal apparatus used for curing the demoulded specimens is shown in Fig. 2. After autoclaving, all the solidified specimens were dried at 80 °C for 24 h before testing.

The solidified rectangular-shaped specimens (15 mm length x 40 mm width x 8 mm height) were used to measure the three point flexural strength employing the Japanese industrial standard (JIS R1601). The tests were conducted in a strength testing machine (EZ Graph, Shimadzu) at a crosshead speed of 0.05 mm/min. Three specimens were tested for each hydrothermal processing condition, and the experimental results presented in this study are the averaged data. After the strength testing, the crushed specimens were investigated for phase analysis by an X-ray diffraction (XRD, MiniFlex, Rigaku) and for microstructure by a scanning electron microscope (SEM S-4100, Hitachi).

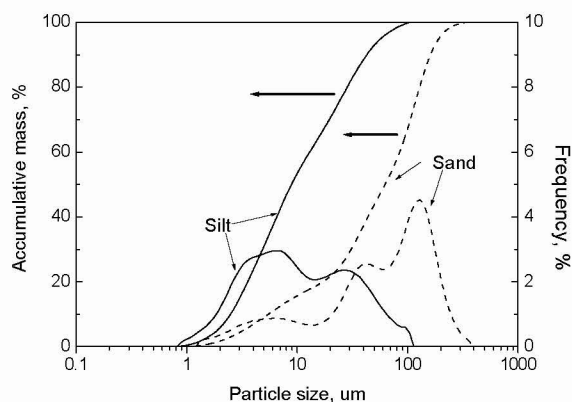


FIGURE 1. Particle size distribution of sediment.

TABLE 1. Composition of the sediment of silt.

	Silt
SiO <sub>2</sub>	55.1
Al <sub>2</sub> O <sub>3</sub>	13.2
Fe <sub>2</sub> O <sub>3</sub>	5.1
CaO	9.0
MgO	2.7
K <sub>2</sub> O	2.6
Na <sub>2</sub> O	1.3
TiO <sub>2</sub>	0.6
Ig-loss	10.4

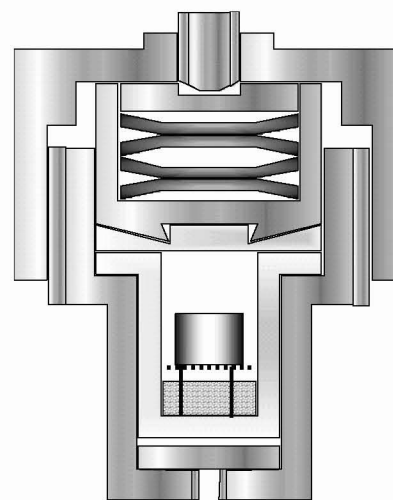


FIGURE 2. Hydrothermal autoclave used for curing compacted specimens.

## RESULTS AND DISCUSSION

Figure 3 indicates the XRD pattern of the silt used. The XRD pattern of the silt confirms the main phases of quartz (SiO<sub>2</sub>), chlorite-vermiculite (Na<sub>0.5</sub>Al<sub>6</sub>(Si,Al)<sub>8</sub>O<sub>20</sub>(OH)<sub>10</sub>·H<sub>2</sub>O), illite-2M<sub>1</sub> ((K,H<sub>3</sub>O)Al<sub>2</sub>Si<sub>3</sub>AlO<sub>10</sub>(OH)<sub>2</sub>) and calcite (CaCO<sub>3</sub>). Because the silt is derived from the loess plateau, its phases consists is similar to that of loess. Kalm et al. [7] reported that loess mineral distribution in the Baoji (in the upper Weihe River) is fairly uniform, and their major components are illite (55-75 %), kaolinite (10-25 %), mixed layer chlorite-vermiculite (10-20 %) and chlorite (<7 %).

Tobermorite is a calcium silicate hydrate mineral of the ideal composition of Ca<sub>5</sub>(OH)<sub>2</sub>Si<sub>6</sub>O<sub>16</sub>·4H<sub>2</sub>O, and can be formed by the reaction between dissolved silica and calcium during hydrothermal process. Because the content of SiO<sub>2</sub> is higher than that of CaO shown in Table 1, slaked lime should be added so as to form tobermorite. Figure 4 shows influence of the slaked lime content on the flexural strength of the solidified specimen. The strength increases with increasing the slaked lime content up to 30 mass%, and then decreases somewhat. At slaked lime of 20-30 mass%, the flexural strength reaches around 23 MPa, which is enough for construction material needed. The molar ratio CaO/SiO<sub>2</sub> (Ca/Si) in the starting material is also plotted in Fig. 4. The Ca/Si molar ratio at the slaked lime content of 30 mass% is very close to the Ca/Si ratio of tobermorite (0.83), thus suggesting that the strength increase may be due to the tobermorite formation.

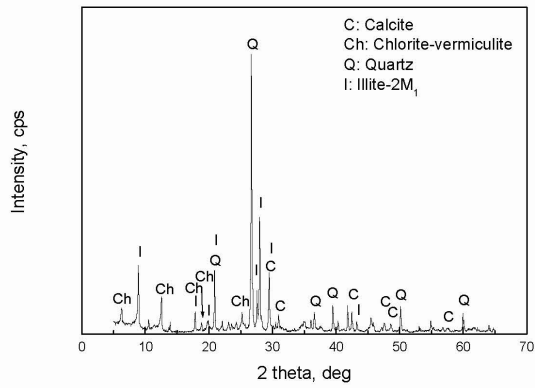


FIGURE 3. XRD pattern of sediment of silt.

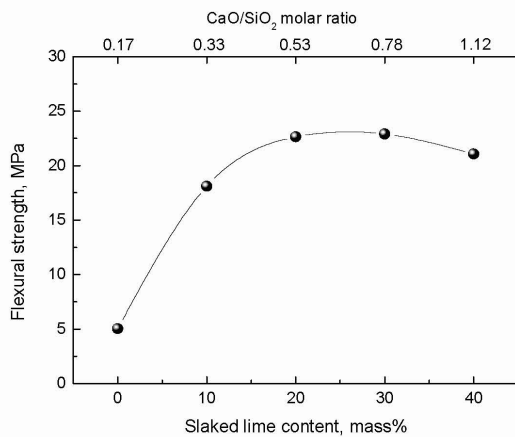


FIGURE 4. Effect of slaked lime content on flexural strength.

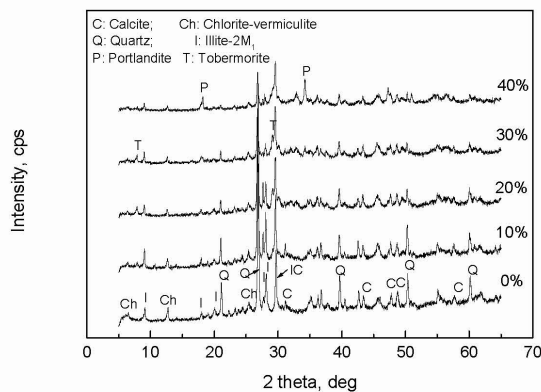
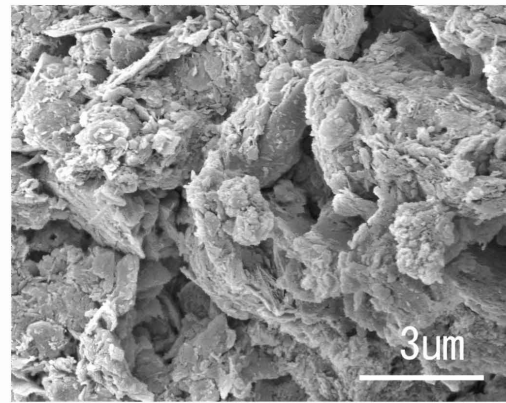
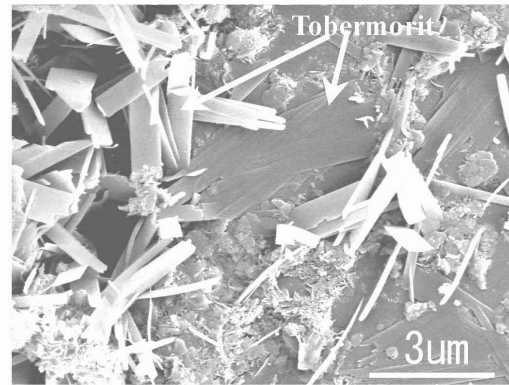


FIGURE 5. Evolution of the XRD patterns with the slaked lime content.



(1)



(2)

FIGURE 6. SEM photographs of the fracture surface of the specimens synthesized with slaked lime 0-10 mass%. (1) 0 mass%; (2) 10 mass%.

The strength development was also investigated by XRD analysis. Figure 5 indicates XRD patterns for the solidified specimens with different content of the slaked lime added. Main phases of quartz, chlorite-vermiculite, illite-2M<sub>1</sub> and calcite are confirmed for the solidified specimen without addition of slaked lime. With addition of slaked lime, a new phase corresponding to tobermorite, as expected, becomes distinct, and the peak intensity of tobermorite appears to increase with the slaked lime content up to 30 mass%, and then decreases. Comparison of the tobermorite peak intensity with the strength development (Fig. 4) suggests that when the CaO/SiO<sub>2</sub> ratio of the starting material was close to 0.83, tobermorite readily formed, and the more the tobermorite formed, the higher the strength. It is notable that the peak intensity of formed tobermorite seems inversely proportional to that of quartz, which reflects that the quartz present in the silt has reacted with added slaked lime to form tobermorite. With addition of slaked lime, a phase corresponding to portlandite (Ca(OH)<sub>2</sub>) forms. At 40 mass% slaked lime added, a higher portlandite peak corresponds with a

lower strength (Fig. 4), which means that the excessive addition of slaked lime exerts a minus influence on the strength of the solidified specimen. The same behavior was also reported for the hydrothermal solidification of coal fly ash [5], and Brunauer et al. [8] also pointed out that  $\text{Ca}(\text{OH})_2$  retards the hydration of cement compounds by forming a protective coating on the surface of unhydrated compounds, and slowing down the hydration.

Figure 6 shows SEM photographs of the fracture surface of the specimen synthesized with slaked lime 0 and 10 mass% and cured at 200 °C for 12 h, respectively. A lot of fibrous tobermorite forms, and the formed tobermorite bonds silt particles together and fills in the spaces between these particles, thus reinforcing the strength of solidified specimen (Fig. 6(2)); while few tobermorite can be found for the specimen without slaked lime added (Fig. 6 (1)). These SEM photographs show that the formed tobermorite looks like fiber reinforcement in the solidified body, thus leading to an enhancement of flexural strength by a factor of four.

## CONCLUSIONS

The sediment of river could be hydrothermally solidified at 200 °C for 12 hrs. The experimental results showed that the sediment could be solidified with tobermorite formation, and addition of slaked lime was favorable to the tobermorite formation, and with addition of slaked lime of 20-40 mass%, the flexural strength reached about 23 MPa. At Ca/Si ratio of 0.83 in the starting material, tobermorite formed readily, and the formed tobermorite exerted a significant influence on the strength development. The more the tobermorite, the higher the strength of the solidified specimens.

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