Mixing Water Treatment Residual with Excavation Waste Soil in Brick and Artificial Aggregate Making

Chihpin Huang[1]; Jill Ruhsing Pan[2]; and Yaorey Liu[3]

Abstract: A large quantity of water treatment residual is generated each year from fresh water treatment plants in Taiwan. Landfill disposal of the nonhazardous sludge is impractical because of the high cost of transportation and an increasing scarcity of landfill sites in Taiwan. The water treatment residual was characterized; the ceramic bodies were prepared and sintered to formulate into building bricks and artificial aggregates. The sintering temperature requirement by the water treatment residual was higher than normally practiced in brick works due to the higher Al_2O_3 and lower SiO_2 content. The excavation waste soil, practically clay, was blended with water treatment residual to improve the brick quality. Under the commonly practiced brick-making condition, up to 15% of water treatment residual could be added to produce first grade brick specified by the National Science Council (NSC). Test results of specific gravity, water absorption, and compressive strength of the artificial aggregates confirmed its applicability in constructions as various degrees of light-weight aggregates.

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Introduction

In Taiwan, the daily production of fresh water is approximately twelve million tons, resulting in a daily production of 24,000–280,000 tons water treatment residual (WTR). This amount is expected to increase dramatically because of the increasing demand for higher-quality water by consumers and the more stringent quality standards regulated by the government. Most WTR is disposed in landfills. This means of disposal is no longer practical in many modern urban municipalities because of the difficulty in finding landfill sites and the costs of operating landfills. Since the government will soon ban landfill disposal, searching for alternatives for sludge disposal has become a priority for the water industry.

Thermal treatment of sludge was originally used for the purpose of volume reduction and stabilization of sludge. The future trend of sludge management, however, is to convert the waste into useful material (Tay and Show 1997; John 2001). A sintering process can bond materials together, resulting in sintered matrices with sufficient strength and extremely low heavy metal leachability (Wang et al. 1998). Ashes of biological sludge and municipal waste incinerator have been recycled into construction materials through this technique. Many studies on reusing sludge ashes as brick materials have been reported in both lab-scale and full-scale applications (Anderson et al. 1996; Okuno 1997; Tay et al. 1997; Wiebusch and Seyfried 1997; Liaw et al. 1998; Sorensen et al. 2001). Sludge ashes have also been made into artificial coarse and fine aggregates for concrete mix (Khanbilvardi and Afshari 1995; Tay et al. 1997; Liaw et al. 1998; Wainwright and Cresswell 2001), permeable blocks and pavement bricks (Nishigaki 2000); and tile (Bernd and Carl 1997). These studies were done on combustion ashes of sewage sludge, industrial wastewater sludge, and municipal solid waste. Although an industrial-scale experiment on brick production with dredge harbor sediments was reported (Hamer and Karius 2002), no studies on resource reuse of the WTR have been reported.

Because of the similar mineralogical composition, the WTR can be a potential substitute for brick clay. Previously, our laboratory had explored the possibility of blending the WTR with dam sediment to make constructional bricks (Huang et al. 2001). Due to depleting resources, there has been a growing trend in converting wastes into profitable products. Excavation waste soil (EWS) is one of the examples. EWS is the soil excavated from the ground before construction. In Taiwan, approximately twenty million tons of EWS are generated each year, which needs to be disposed of properly. Many local brick works have been incorporating EWS as brick material. In this study, we blended the WTR with the EWS to make bricks and artificial aggregates. The characteristics of the products were examined and evaluated according to the Chinese National Standard (CNS) specification for various degrees of bricks and aggregates, as shown in Table 1. The result will be adopted in a large-scale study on producing marketable constructional products from the WTR.

Materials and Methods

Raw Materials for Sintering

WTR and EWS were the raw materials for sintering. The WTR was the dried sludge cake obtained from the Chin-Tan Water

[1]Professor, Institute of Environmental Engineering, National Chiao Tung Univ., 75 Po-Ai St., Hsinchu, Taiwan, 300 (corresponding author).

[2]Associate Professor, Institute of Environmental Engineering, National Chiao Tung Univ., 75 Po-Ai St., Hsinchu, Taiwan, 300.

[3]Graduate student, Institute of Environmental Engineering, National Chiao Tung Univ., 75 Po-Ai St., Hsinchu, Taiwan, 300.

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Table 1. CNS382.R2002 Brick Criteria

Bricks	Water absorption (%)	Compressive strength (kg/cm^2)	Apparent density (g/cm^3)
First degree	<15	>150	1.8–2.0
Second degree	<19	>100	1.8–2.0
Third degree	<23	>75	1.8–2.0
Pavement bricks	<2	>500	2.2–2.6

Treatment Plant in the northern part of Taiwan, in which polymeric aluminum chloride was used in the coagulation process. The EWS was obtained from a local brick works. Basic characteristics of the raw materials, such as pH, water content, combustible matter, ash content, and concentrations of heavy metals and other chemical components, were determined. The water content, combustible matter, and ash content were determined following the procedure NIEA 203.00T–205.0T regulated by the Environmental Protection Agency-Republic of China. The chemical composition was identified and analyzed by using the energy dispersive spectrometer and the inductively coupled plasma-atomic emission spectrometer, respectively, and the heavy metal content was determined with the atomic adsorption spectrophotometer. The softening point, melting point, and pouring point (PP) were determined with a melting kiln model CAF9701 by Carbolite. The mineralogical composition was determined with the x-ray diffraction of MXP18, a product of MAX Science.

Preparation of Bricks and Artificial Aggregates

Before sintering, the raw materials were dried in the oven (105°C for 24 h), pulverized, and sieved. Materials between Sieve No. 30 and No. 200 were collected for test sample. The treated samples were mixed and blended with appropriate amount of water, and then compacted and molded with a Carver No. 3851 press to form a quadrate die bolster of $6\times3\times2$ cm. The compact specimens were fired in the combustion chamber of an electrical kiln, a Naber N100H furnace, under various firing temperatures and times.

To make artificial aggregates, the WTR was pelletized into a ball of approximately 2 cm in diameter. The ball was dried in the oven at 105°C for 24 h followed by the sintering process.

Brick Analysis

Physical characteristics of the sinter, namely, loss on ignition (LOI), firing shrinkage, water absorption, density, and compressive strength, as well as the toxicity characteristic leaching procedure (TCLP), were analyzed.

- *LOI*. The LOI is calculated as

$$\mathrm{LOI} = \frac{W_0 - W_1}{W_0} \times 100\%$$

  in which W_0 and W_1=weights of the specimen before and after sintering, respectively.
- *Firing shrinkage*. The firing shrinkage is calculated as follows:

$$\text{Firing shrinkage} = \frac{V_0 - V_1}{V_0} \times 100\%$$

  in which V_0 and V_0=volumes of the specimens before and after sintering, respectively.
- *Water absorption*. Water absorption is calculated from the amount of water absorbed by the brick after immersion in water for 24 h,

$$\text{Water absorption}(\%) = [(W_1 - W_0)/W_0] \times 100\%$$

  where W_0 and W_1=weights of the specimens before and after the immersion.
- *Bulk density*. Bulk density is calculated from the weight, W_S, and the total volume, V_S, of the brick

$$\text{Bulk density} = W_S/V_S\ (\mathrm{g/cm^3})$$

- *Compressive strength*. The unconfined compressive strength is the maximum compressing force a sinter can withstand before it breaks. The bench-scale bricks were tested according to the ASTM C39-81 procedure. The sinter was placed vertically on the platform of the press, a model 50-C41H4 press machine made by CONTROLS, Italy, and was pressed until it was crushed. The compressive strength of the sinter is the compressing force (kg force) divided by the pressed area (cm^2).

Table 2. Characteristics of Water Treatment Residual and Excavation Waste Soil

Parameters	Water treatment residual	Excavation waste soil
pH	6.59	6.83
Moisture content (%)	6.27–11.73	2.87
Ash content (%)	74.82–86.64	93.63
LOI[a] (%)	7.09–13.45	3.50
Volatile matter[b] (%)	5.35	2.75
Pouring point (°C)	1,520	1,412

Note: LOI=loss on ignition.

[a]Fired at 800±50°C for 3 h.

[b]Combusted at 550±50°C for 3 h.

Evaluation of Artificial Aggregates

The characteristics of the artificial aggregates, including water absorption and specific gravity, were determined. The sintered balls were then used as the coarse aggregate and made into cement mortar, in which the natural sand was the fine aggregate. The concrete mixing ratio of 1:1:2 for cement: fine aggregate: coarse aggregate was adopted since a preliminary experiment proved that such combination resulted in the highest concrete strength. A water-to-cement ratio of 1:2 was used in casting the concrete. After removing from the mold, the cement mortar was cured by immersing in potable water for 7, 14, and 28 days. The compressive strengths of the 7-day, 14-day, and 28-day concrete specimen were tested.

Results and Discussion

Basic Characteristics of Raw Materials

The basic physical properties of the WTR and EWS are summarized in Table 2. Both samples are low in organic content and high in ash content. The low LOI and volatile matter of both EWS and WTR suggest that incineration is not necessary before sintering. The required sintering temperature can be estimated from the PP of the material. They are approximately 60 to 80% of the PPs. The PPs of WTR and EWS were 1,520 and 1,412°C, respectively. This can be explained by their differences in chemical compositions, as given by Table 3. The major chemical composi-

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Table 3. Chemical Compositions of Water Treatment Residual, Excavation Waste Soil, and Clay

	(W/W) (%)		
Composition	Water treatment residual	Excavation waste soil	Clay
SiO_2	52.75	60.37	61.95
Al_2O_3	20.15	15.42	16.95
Fe_2O_3	6.75	7.25	9.27
K_2O	3.69	2.91	0.14
Na_2O	0.872	0.66	0.02
CaO	0.3	0.32	0.45

Note: W/W=weight of compound/weight of raw material.

tions of WTR and EWS were silicon, aluminum, and iron oxides. Since the chemical compositions of the EWS and clay are extremely similar, the EWS can be an excellent substitute for brick clay. The WTR, on the other hand, has much higher Al content and lower SiO_2 content than the EWS. Since the strength of the brick depends largely on silica, the strength of the brick made from WTR may be impaired. Since the melting point of alumina, about 2,300°C, is the highest among all compositions, sintering of the WTR will consume substantially more energy.

Properties of Bricks Made from Excavation Waste Soil and Water Treatment Residual

Sintering environment affects the quality of the sinter critically. The effect of sintering temperature and time were tested, using compressive strength as an index. Fig. 1 shows that compressive strength increased with the increasing sintering temperature. Although longer sintering produced stronger bricks, the difference between 3 and 6 h was so insignificant that 3 h of sintering time should be sufficient for the bolster of size $6 \times 3 \times 2$ cm to produce a satisfactory brick in the temperature range from 800 to 1,100°C. Therefore, 3 h of sintering time was chosen for the rest of this study. Bricks were first made from the WTR and EWS, separately. The brick property was evaluated for five areas: LOI, firing shrinkage, water absorption, bulk density, and compressive strength.

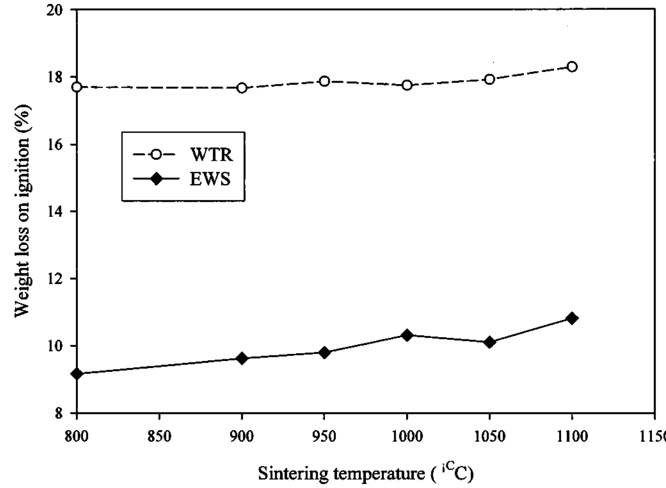

Fig. 2. Weight loss on ignition of excavation waste soil and water treatment residual at various sintering temperatures

Loss on Ignition

The weight loss of the specimens during sintering is mostly due to the organic compounds and the inorganic $CaCO_3$. Wang et al. (1998) indicated that the organic compounds in the compact specimen can gasify and/or oxidize to CO_2 and H_2O, while the $CaCO_3$ decomposes into CO_2 and CaO at a high temperature. As indicated in Fig. 2, the WTR and EWS exhibited a distinctively different extent of LOI, 18% for the WTR versus 10% for the EWS. And, varying sintering temperature from 800 to 1,100°C has a minimal effect on the LOI for both waste soils. This was because most of the volatile substances had escaped before reaching 800°C.

Firing Shrinkage

Too much volume shrinkage can cause the distortion and breakage of bricks. Therefore, the dimensional change during sintering is another way of monitoring the sinter quality. Unlike the sintering of incinerator ashes, no swelling occurred during the course of sintering. Fig. 3 shows that the shrinking of EWS sintering is much milder than that of WTR. At 950°C, the temperature commonly practiced in brick works, the firing shrinkage of the EWS sinter is insignificant. Above that, it increases with the sintering

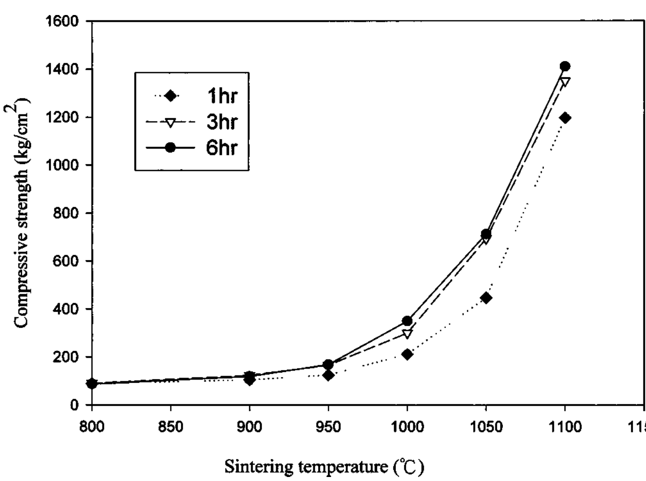

Fig. 1. Compressive strength versus firing temperature of excavation waste soil at various firing times

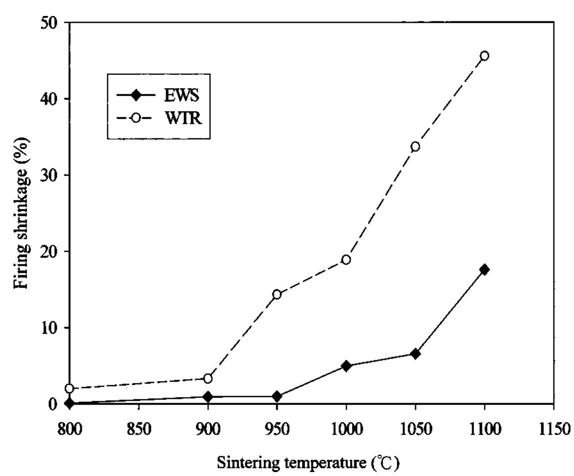

Fig. 3. Firing shrinkage of excavation waste soil and water treatment residual brick specimens at various sintering temperatures

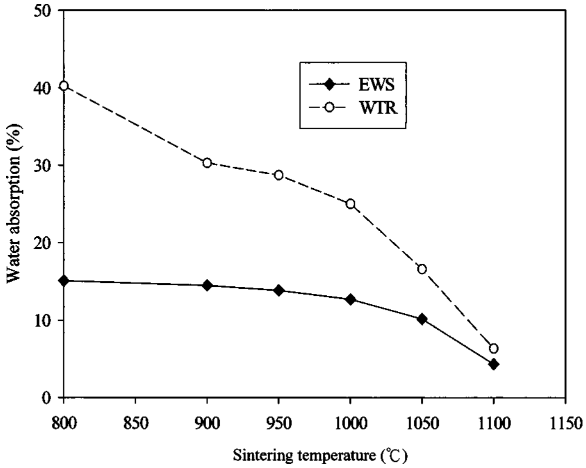

Fig. 4. Water absorption of excavation waste soil and water treatment residual brick specimens at various sintering temperatures

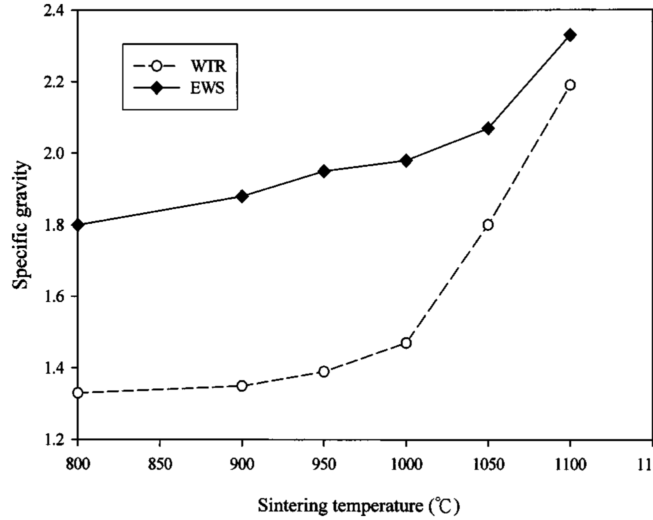

Fig. 5. Bulk density of excavation waste soil and water treatment residual brick specimens at various sintering temperatures

temperature. An 18% volume reduction was observed at 1,100°C. The change in the sintering of the WTR is much more dramatic. Significant shrinkage began to occur at 950°C, and a 45% volume reduction was determined at 1,100°C. The extent of densification is much higher than that of the corresponding LOI, as shown in Fig. 2, which suggests the formation of a new crystalline phase.

Water Absorption

Water absorption is the weight of moisture in the pores to the weight of the sintered specimen. It is a function of densification and open pores. Absorption of moisture is one brick quality rationalized by the NSC. High water absorption resulted in moss contamination and recrystallization of the liquid $CaCO_3$ on the brick surface, which shortened the life of the brick as a pavement. The sintering process closes the open pores of the sintered body, resulting in less water absorption. Fig. 4 shows that water absorption decreases with increasing sintering temperature. The brick made from the WTR shows a progressive reduction in water absorption with the increased firing temperature. Since the NSC limit for water absorption of the first degree bricks is 15%, a sintering temperature of 1,050°C was required. On the other hand, the water absorption of the EWS brick was substantially low and insensitive to sintering temperature.

Bulk Density

Bulk density is the ratio of the weight-to-total volume of the mass and the open pores. Consequently, the changes in both the mass density and the porosity affected the bulk density of the sintered specimens. During the sintering process, the distance between the particles in the sinter decreased with the increasing temperature. The viscous phase started to appear, which was called neck growth. The bulk density increased with the increasing sintering temperature due to densification. As shown in Fig. 5, for EWS, the CNS bulk density *f* criteria or primary bricks, 1.5 g/cm^3, can be achieved at as low as 800°C. To meet the same criteria, the WTR will have to be sintered at 1,000°C. The EWS contained a higher amount of Fe_2O_3, 7.25% in comparison with the 6.75% of the WTR, which can lower the sintering temperature and increase the melting of the glass phase.

Compressive Strength

Compressive strength determines the potential for constructional application of the bricks. Compressive strength affects the porosity, pore size, and types of crystallization. The CNS criteria, for first, second, and third degree, and pavement bricks are 150, 100, 75, and 500 kgf/cm^2, respectively, given in Table 1. Fig. 6 shows that the compressive strength increases with the sintering temperature. There appeared to be a change in this dependency between 900 and 1,000°C. The increase in compressive strength above 1,000°C was much more dramatic, especially for the EWS bricks. It suggested that 900°C was the starting temperature for neck growth. To meet the CNS standard for first-degree bricks, the EWS must be fired at 950°C, in contrast to 1,050°C for the WTR.

In summary, direct reuse of WTR in brick making may not be economically sound because of the extra energy required to produce quality bricks. Since the EWS was apparently a suitable substitute for brick clay, the WTR was blended into the EWS in various proportions as raw material for bricks. Their brick characteristics were examined.

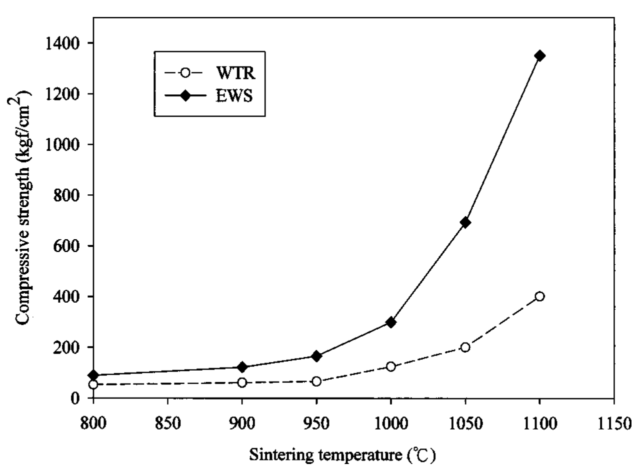

Fig. 6. Compressive strength of excavation waste soil and water treatment residual brick specimens at various sintering temperatures

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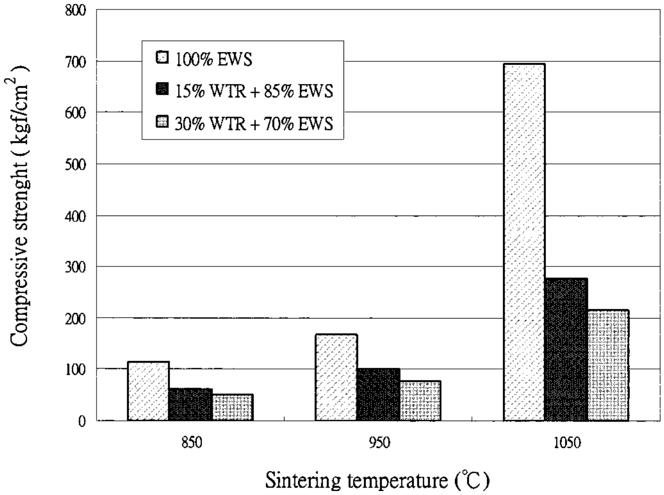

Fig. 7. Compressive strength of brick specimens from various additions of water treatment residual at different firing temperatures

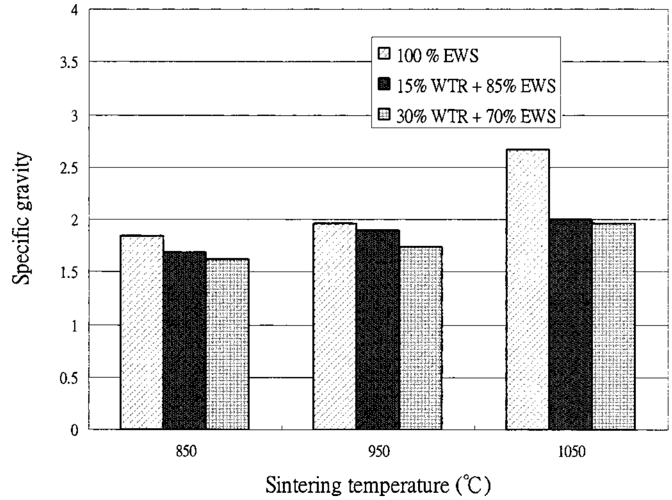

Fig. 9. Bulk density of brick specimens from various additions of water treatment residual at different firing temperatures

Brick Properties of Mixed Waste Solid

Various amounts of the WTR, 0 to 30% on weight basis, were mixed with the EWS to make bricks. The brick qualities were evaluated on their compression strength, bulk density, and water absorption.

Compressive Strength

Fig. 7 shows the variation of compressive strengths with the addition of WTR. At 950°C, bricks containing 15 to 30% WTR can be used as second- and third-degree construction bricks. When the sintering temperature was increased to 1,050°C, bricks from all three samples met the first-degree bricks criteria. Therefore, a large amount of WTR can be treated this way if energy consumption can be overcome.

Water Absorption

The content of WTR in the brick mixture slightly affects water absorption, as shown in Fig. 8, in comparison with its effect on compressive strength. The standard for the first-degree brick can be met by a 15% WTR addition at 950°C sintering or 30% WTR addition at 1,050°C sintering. The result also suggests that bricks made this way are not suitable for pavement.

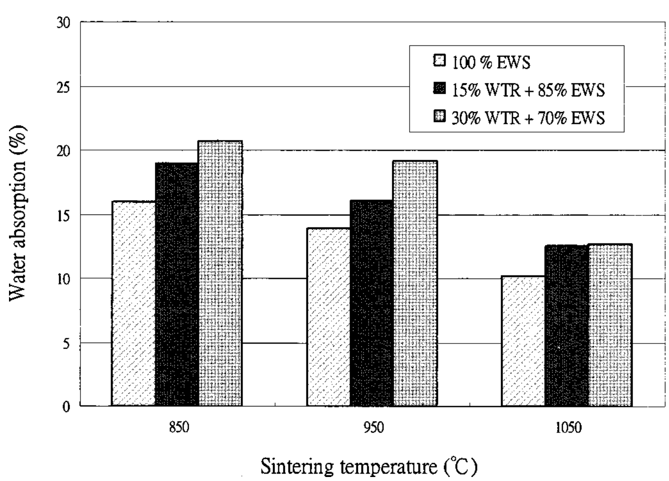

Fig. 8. Water absorption of brick specimens from various additions of water treatment residual at different firing temperatures

Bulk Density

The change in bulk density signifies the degree of densification. As indicated in Fig. 9, the addition of WTR had a minimal impact on the bulk density of the sinters. Although raising the sintering temperature increased the sinter density, in general, the effect was also very limited. Densities of all sintered slags—except those from the 1,050°C sintering of EWS—were lower than 2 g/cm^3, which suggested the use as lightweight coarse aggregates for construction purposes. The WTR was made into aggregates and its property was evaluated.

Evaluation of Aggregates Made from Water Treatment Residual

To function as a constructional aggregate, the aggregate must be dimensionally stable with suitable density and water absorption, and not present any harmful reaction with the hydrated cement phase constituents. The concrete mortar must have compatible mechanical strength. The TCLP result (not shown here) has confirmed that no detectable hazardous element was released from the aggregates. The properties of the sintered aggregates would be discussed in terms of volumetric specific gravity and water absorption, and the compressive strength of the concrete specimen.

Volumetric Specific Gravity

The aggregate properties made from mixed waste solids were evaluated for potential reuse as light aggregates. Specific gravity was the most critical parameter in the evaluation since it domi-

Table 4. Specific Gravity and Water Absorption of Artificial Aggregates Made from Water Treatment Residual

	Sintering temperature		
Properties	1,000°C	1,050°C	1,100°C
Specific gravity	1.12	1.71	1.78
Water absorption (%)	37	15.48	14.47

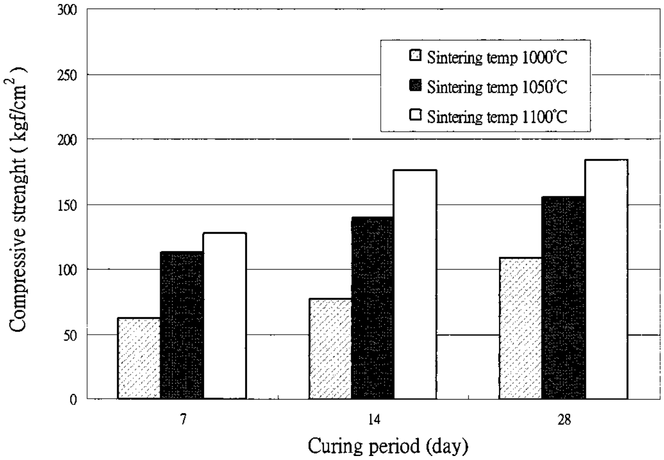

Fig. 10. Compressive strength of concrete specimen prepared from aggregates from different firing temperatures and various curing times

nated the usage of the sintered product. Table 4 summarizes the specific gravities of artificial aggregates made from the WTR at various sintering temperatures. They range from 1.12 to 1.78, meeting the criteria for lightweight aggregates.

Water Absorption

Water content is extremely important during cement mixing. Water absorption of aggregates affects the water available during concrete mixing and the hardening process of the concrete. As shown in Table 4, 37% water absorption was determined for the 1,000°C-sintered aggregates. No significant change in water absorption rate was observed above 1,050°C.

Compressive Strength of Concrete Specimen

The concrete specimens were prepared by blending the artificial lightweight aggregates with natural sand and cement in a weight ratio of 2:1:1 for natural sand: light weight aggregate: cement. The specimens were cured for 7–28 days in the curing room. Their compression strengths were tested. The results were presented in Fig. 10. To meet the standard for constructional concrete, the specific gravity of the lightweight aggregate was 1.4–2.0 g/cm^3 and the compressive strength of the concrete was from 175 to 420 kgf/cm^2. Only aggregates made from 1,100°C sintering met this requirement.

Conclusion

Incineration was not required before the sintering process of WTR and EWS due to their low organic contents. The EWS resembled the brick clay in its chemical composition and, hence, sintering property. A higher sintering temperature was required by the WTR to achieve a qualified brick property due to its lower silica and higher alumina contents. The brick property of the WTR sinter could be enhanced by the addition of the EWS. The firing temperature dominated the percentage of WTR which could be added in the mixture. By operating at the temperature commonly practiced in the brick kiln, 15% was the maximal WTR addition to achieve first degree brick quality. Artificial aggregate could be produced from the WTR employing granulation and sintering techniques. Within the sintering temperature range studied, the aggregates fell in the light-weight category. The concrete strength indicated that only the artificial aggregates prepared by sintering at 1,100°C were comparable to those using other commercially available light-weight aggregate.

Acknowledgment

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