Utilizing Wastewater Treatment Sludge in Mortar to Minimize the Carbon Footprints

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Abstract

Cement production from the construction industry significantly contributes to global carbon emissions. Simultaneously, unsustainable sludge disposal methods from water treatment facilities have become an alarming threat to the environment nowadays. To tackle both issues, this research aims to investigate the potential of utilizing untreated wastewater treatment sludge (WWTS) as a partial cement replacement in mortars. Unlike previous studies that used energy-intensive treatment processes, this research emphasizes adopting untreated WWTS collected from the water quality control plant in Bangkok, Thailand, to enhance sustainability gains. In this study, five mortar mixes with WWTS replacement percentages of 0%, 5%, 10%, 15%, and 20% by weight of cement were prepared and tested. Physical properties of mortars were assessed by means of flowability and setting time. Mechanical performance of mortars was examined through compressive strength testing at 3, 7, and 28 days. Furthermore, a comparative analysis of carbon emissions between control mortar and WWTS-incorporated mortars was carried out in evaluating the environmental benefits of this study. By utilizing untreated WTS and analyzing its effects on mortar properties, the various replacement levels of cement with WWTS that balance mortar's performance and environmental benefits were determined. The findings of this study will contribute to sustainable construction practices by offering twofold benefits, not only in the reduction of cement consumption but also in providing an environmentally friendly solution for WWTS disposal.

Keywords: Wastewater Treatment Sludge, Cement Replacement, Carbon Footprints, Sustainability

1. Introduction

At present, the global construction industry is under mounting pressure to algin properly with sustainable goals and carbon emissions from the cement production has become one of the major threats to construction sustainability. Cement production is responsible for the release of more than 2 Gigatons carbon dioxide (CO_2) annually [1], and 12% to 15% of the world's industrial energy is being utilized for cement manufacturing [2]. If the cement production maintains its existing trends, the yearly CO_2 emissions from cement production industry are projected to reach 1.4 –3.8 gigatons by the year 2050 [3]. To alleviate carbon footprints from cement production, alternative approaches such as substitution of eco-friendly materials or industrial waste products with cement in mortar or concrete mixing are in desperate demand.

Likewise, massive quantities of sludge disposal from water and wastewater treatment plants threaten the economy and environmental aspects because of limited sustainable disposal approaches [4]. Prevalent methods to dispose of sludge are landfilling and use in agriculture, but these methods are losing their effectiveness due to scarce disposal areas. Another practical treatment option for wastewater sludge management is incineration, but the leftover ash from the incineration process is still a concern for further disposal consideration [5]. In developing countries, sludge from treatment plants is discharged into creeks, drains, streams and rivers so that the environment gets greatly impacted [6]. As organic compounds and heavy metals such as lead (Pb), manganese (Mn), copper (Cu), chromium (Cr) and zinc (Zn) constitute water treatment sludge, water in nature may get contaminated by their leaching [7].

To address the carbon emissions caused by cement production and to adopt a more sustainable method in managing water and wastewater treatment sludge in the modern civilized era, some researchers [8-12] have attempted the twofold advantageous method of utilizing water treatment sludge as a supplementary cementitious material in concrete and mortar. However, former studies have been done by treating wastewater treatment sludge through calcination, which poses high energy consumption and milling, which is also an energy-intensive process for bulk production. As a result, those studies might not have attained optimum sustainability gain while utilizing WWTS.

In addition, Thailand's construction industry is not only an important driver for economic development but also a major contributor to greenhouse gases (GHG). According to GHG emissions report 2024 [13], Thailand had total GHG emissions of 440.78 metric tons and total CO_2 emissions of 274.16 metric tons in 2023. As the implementation of infrastructure projects in Thailand depends heavily on the production of cement and the use of reinforced concrete, the construction sector is facing challenges, including limited integration in reducing carbon footprints [14]. Furthermore, existing literatures have demonstrated that the quantity and characteristics of sludge mainly depend on the source and quality of raw water or raw wastewater and the treatment process applied [10,15,16], this opens a significant gap in the research area specific to Nong Khaem water quality control plant which has total serving area of 44 km^2 including Nong Khaem, Pasi Charoen and Bang Kae districts and treatment capacity of 157,000 m^3 per day. Despite former researchers in Thailand focusing on the incorporation of sludge in various applications such as the production of lightweight interlocking block panels [17], the development of lightweight concrete blocks [18], the manufacture of hollow concrete blocks [19], sludge-incorporated cement grout in rock fractures [20], and the manufacturing of fired clay bricks [21], no comprehensive study has been conducted on the partial replacement of cement with WWTS in mortar, in combination with a carbon emissions comparative measure of mortars.

This study intends to examine the properties of mortar mixes prepared by partially replacing hydraulic cement with wastewater treatment sludge (WWTS) collected from Nong Khaem water quality control plant. Five types of mortar with replacement percentages of 0% (control mix), 5%,10%,15% and 20% on the weight of hydraulic cement were mixed and physical, and mechanical performances of each mortar mix were analyzed through flowability, setting time and compressive strength testing. Besides, the implementation of comparative analysis on carbon emissions between control mortar and WWTS-incorporated mortars by analyzing per kilogram CO_2 on each material in mortar mixes makes it possible to assess the viability and environmental merit of utilizing untreated wastewater treatment sludge as a partial cement substitution in mortars. This research encourages the enhancement of construction sustainability by reducing the carbon footprints caused by cement production and by offering alternative options for the valorization of wastewater treatment sludge (WWTS).

2. Methodology

2.1 Materials

2.1.1 Wastewater treatment sludge (WWTS)

The wastewater treatment sludge (WWTS) utilized in this study was collected from Nong Khaem water quality control plant located in Bangkok, Thailand. With treatment capacity of the plant is 157,000m^3 per day, sludge from the mentioned water quality pant can be expected to supply for bulk production if filed applications are adopted. To preserve optimum sustainable level of the research, the treatment processes such as oven drying, calcination, and mechanical grinding steps on WWTS were eliminated. The wastewater treatment sludge (WWTS) was collected from the bins of treatment plant and dried at room temperature for a prolonged period of more than 1 year. The sieve analysis of WWTS was conducted to examine the particle size distribution through ASTM C136-06 standard [22]. Fig. 1 represents the particle size distribution graph of WWTS after drying at room temperature and Fig.3 shows the WWTS after drying at room temperature. The sludge particles used in this study ranged in size from 4.75mm to 75µm . The specific gravity of WWTS in this study was 1.19.

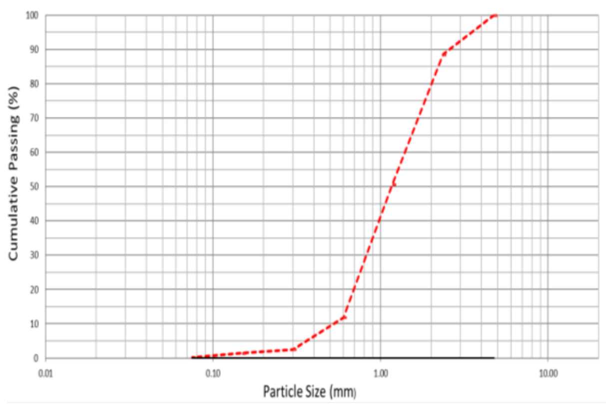

Fig. 1 Particle Size Distribution of WWTS

2.1.2 Cement

Hydraulic cement (Type GU) conforming to ASTM C1157/C1157M-17 [23] was used in this experimental study. The cement was acquired from the local market having a specific gravity of 3.04.

2.1.3 Sand

The conduct of this research used natural sand and sieve analysis of the sand was conducted in compliance with ASTM C136-06 [22]. The specific gravity of sand was found to be 2.55 and its water absorption was 0.644%. The grading curve of natural sand utilized in the study is shown in Fig. 2 along with the standard grading requirement limits of natural sand specified by ASTM C144-11 [24].

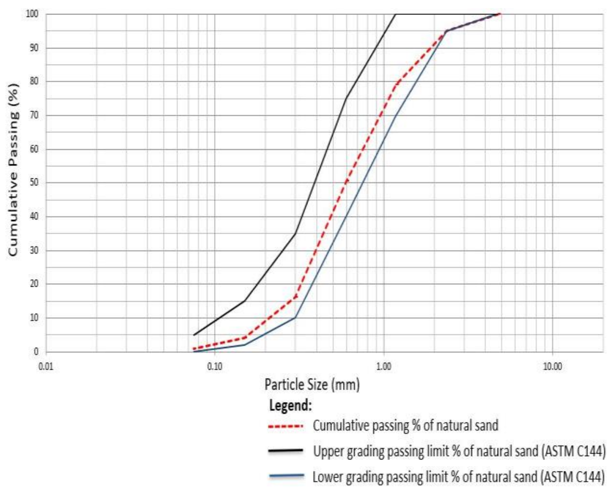

Fig. 2 Particle Size Distribution of Natural Sand

2.1.4 Water

In this experimental study, the water added in mixing mortars was portable tab water suitable for mortar mixing.

Fig. 3 Wastewater treatment sludge (WWTS) after drying at room temperature for more than one year

2.2 Mix proportion

Five distinctive proportions of WWTS were set to substitute a portion of the weight of the hydraulic cement in the mortars. All mortar mixes were kept at a water-binder ratio of 0.375, and the ratio of binder to sand was fixed to 2.125. The water-binder ratio of 0.375 was chosen to optimize compressive strength, which can be referenced based on applications with different strength demands. To evaluate the effectiveness of the WWTS incorporated mortars, the mortar without the WWTS was set as a reference mortar (CM0). The levels of partial replacement of WWTS for hydraulic cement in the mortar mixes were set to 5%, 10%, 15%, and 20%. The mortars were then named according to their degrees of replacement, designated as SM5, SM10, SM15, and SM20, respectively. The mix proportion of the five different classes of mortars to a cubic meter is given in Table 1.

Table 1 Mix proportions of five types of mortars for 1m^3

Mix Code	WWTS Replacement (%)	WWTS (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)
CM0	0	0	651.85	1385.18	244.44
SM5	5	32.59	619.26	1385.18	244.44
SM10	10	65.19	586.66	1385.18	244.44
SM15	15	97.78	554.07	1385.18	244.44
SM20	20	130.37	521.48	1385.18	244.44

2.3 Mixing and samples preparation

An electric mixer of 10L capacity was used to mix all types of mortars. Water and sand were first mixed for 45seconds and then WWTS and sand were incorporated into the cement mix. The mixing was further processed up to 90 seconds after adding all materials to ensure the thorough blending. For setting time and flowability testing, fresh mortar was taken according to reference testing procedures for each mortar mix. For compressive strength testing, 15 numbers of 50 x 50 x 50 mm cube specimens for each mortar mix were cast and cured. Fig. 4 shows the mortar specimens for compressive strength testing.

Fig. 4 50 x 50 x 50 mm specimens for compressive strength test

2.4 Flowability test

Using a standard flow mold, the flowability of each mortar mix was determined in compliance with ASTM C1437-20 [25]. The flow test of this research is presented in Fig. 5. First, the flow table was thoroughly cleaned and dried, and the flow mold was placed in the middle of the table surface. Then, the first layer of mold was filled with 25 mm thick mortar by compacting 20 uniform tamps. Following the first layer, the second layer was added until the slight overflowing of mortars occurred. The table was then dropped 25 times in 15 seconds to spread the mortar and the diameter of the mortar was measured using four predetermined lines using a caliper. The flow percentage of each mortar mix was computed using Eq. (1).

$$Flow\% = \frac{D - D_0}{D_0} \times 100 \quad (1)$$

Where:

D = the average diameter of four readings in mm

D_0 = the original inside base diameter of the mold in mm

Fig. 5 Flowability test of mortar

2.5 Setting time

Only the initial setting time of each mortar mix was examined through ASTM C191-08 [26]. Fig. 6 illustrates the setting time test of mortar. In this experiment, manually operated Vicat needle apparatus was utilized, and the commencement of the penetration test started after 30 minutes of mortar mixing. The penetration testing was performed until a penetration depth of 25 mm or less had been achieved. All penetration results were recorded, and interpolation was applied to calculate the precise time of 25 mm penetration occurrence when needed. The initial setting time was then calculated based on the time gap between the initial time at which cement contacted water and the time of 25 mm penetration.

Fig. 6 Initial setting time test of mortar

2.6 Compressive strength testing

The compressive strength test was performed on 3 numbers of 50 × 50 × 50mm cube specimens for control mortar as well as 4 types of untreated WWTS incorporated mortars at 3days, 7days and 28days. The MATEST S.p.A. Treviolo 24048 model compression machine with a maximum capacity of 3000kN was used to perform the testing, and the test method was according to ASTM C109/C109M-16a [27]. During compressive strength testing, the load was applied at the rate of 1200 N/s until the occurrence of the failure of test specimens. Fig. 7 represents the compressive strength testing of mortars. As a set of 3 specimens for each mortar mix was tested for each mentioned date of 3days, and 28days, the average compressive strength was calculated and reported to the nearest 0.1 MPa.

Fig. 7 Compressive strength test of mortar specimens

2.7 Cabon emissions of mortars

Carbon emissions parameters of this study were analyzed based on the carbon emissions while preparing each raw materials used for mixing mortars. As per previous studies [28,29],raw materials like wastewater treatment sludge and fly ash contribute zero carbon emissions as they are by-product of treatment plants. As this study eliminated energy-intensive processes such as high temperature calcination, grinding, and oven-drying of WWTS, these factors can be neglected while considering carbon analysis of WWTS and only cement, sand and water were taken into account for carbon emissions. The emissions factors for these materials were referenced from the previous literatures as shown in Table 2.

Table 2 Carbon emissions factors of raw materials

Materials	Emission factors (kg CO2/kg)	References
Cement	0.951	[30]
WWTS	0	[28,29]
Sand	0.0026	[31]
Water	0.000196	[32]

3. Results and discussion

3.1 Flowability

The flow test results of control mortar and four WWTS incorporated mortars are illustrated in Fig. 8. It is noticeable that the flow percentage of mortars decreases when the replacement percentage of untreated WWTS in mortars increases. The flow percentage of mortars with 5% cement replacement with untreated WWTS was 25% less than that of control mortar, whereas the flow percentage of mortars with 10%, 15%, and 20% of untreated WWTS in substitution of cement indicated 40%, 55.6%, and 66.7% less than that of the control mortar. This reduction in flow might be due to the increased friction between particles caused by the addition of wastewater treatment sludge (WWTS). Moreover, the untreated and coarser particles of WWTS incline towards the absorption of more water and obstruct the smooth flow of fresh mortars. This result is consistent with the findings of Lee [4], using treated and untreated wastewater sludge, and Vouk et al. [33], who applied incinerated sewage sludge ash in mortars because both studies revealed that increasing the sludge portion caused a reduction in mortar workability. From this study, it is suggested that SM5 can be considered in applications where moderate flow is acceptable, as its flowability differed only 25% from that of control mortar. SM10 can be used for certain work where some reduction in workability can be tolerated. For specialized applications where low flow is advantageous, such as 3D printing or extrusion-based construction methods, SM15 and SM20 might be suitable options.

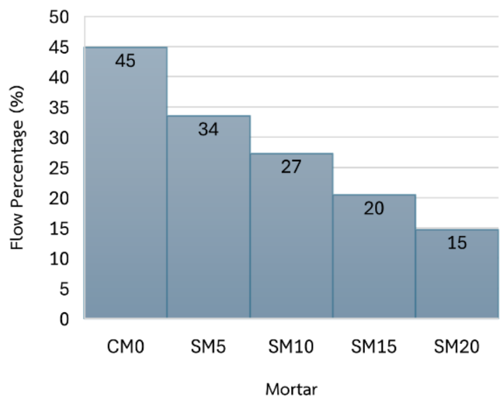

Fig. 8 Flow percentage of mortars

3.2 Setting time

The initial setting time of control mortar and WWTS incorporated mortars with 5%, 10%, 15% and 20% replacement of cement were 73mins, 74mins, 80mins, 108mins and 126mins, respectively. Fig. 9 shows the initial setting time of 5 types of mortars. The study revealed that the delay in initial setting time of mortar became more significant while more than 10% of wastewater treatment sludge was incorporated as partial cement replacement in mortars whereas the initial setting time of mortars with 5% and 10% of WWTS appears to be only slightly different with that of the control one.

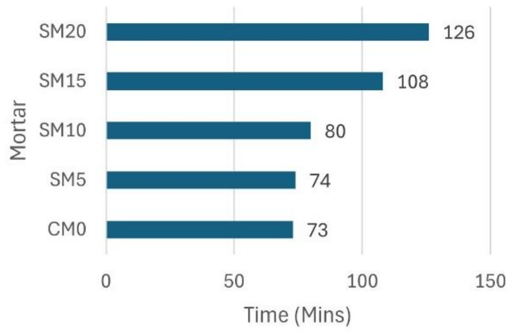

Fig.9 Initial setting time of mortars

This trend in initial setting time suggests that organic compounds and coarser particles in the untreated WWTS disturb the hydration process when the higher amount of cement is replaced by the WWTS. This finding aligns with the research result of mortar with untreated wastewater sludge conducted by Lee [4]. The current study also provides consideration while applying WWTS mortars in various circumstances. As the initial setting time of SM5 is almost similar the control CM0, it is ideal for projects where minimal delay in setting is acceptable and some environmental benefits are desired. The SM10, whose initial setting time is slightly longer than the control, could be intended for projects where a moderate delay in setting up can be accommodated. For applications where a longer setting time is beneficial, such as in hot weather conditions or when more time is required for finishing, SM15 and SM20 might be ideal.

3.3 Compressive strength

The compressive strengths of mortar specimens for each mortar type examined at 3 days, 7 days, and 28 days are presented in Table 3 and Fig. 10. As per results, control mortar and mortar with 5% WWTS substitution of cement exhibited a slight reduction in compressive strength, resulting in 19.57% at 3 days, 15% at 7 days, and 10.74% at 28 days. In contrast, mortars with higher levels of cement replacement developed more pronounced reductions in strength across all testing ages. The replacement of 10% cement with WWTS in mortar led to a 48.5% strength reduction in 3 days, 47.8% in 7 days, and 37.96% at 28 days. The mortars with 15% and 20% cement substitution with WWTS tend to show even greater declines approximately 50% in compressive strength when making comparisons with that of control mortar at all testing intervals.

Table 3 Compressive strength of mortars at 3, 7 and 28 days

Mix code	Compressive strength (3days)	Compressive strength (7days)	Compressive strength (28days)
CM0	45.5 MPa	53.4 MPa	59.8 MPa
SM5	36.6 MPa	45.4 MPa	53.4 MPa
SM10	23.4 MPa	27.9 MPa	37.1 MPa
SM15	21.5 MPa	24.8 MPa	30.9 MPa
SM20	14 MPa	20.5 MPa	25.2 MPa

The findings in compressive strength highlight the considerable alteration in mechanical property of mortars when WWTS is added as partial cement replacement. This observation suggests that untreated wastewater treatment sludge (WWTS) has lower reactivity and weaker binding properties as the sludge did not undergo thermal intensive treatments to activate pozzolanic reactions. This inclination in compressive strength is generally consistent with the findings of treated and untreated wastewater sludge with 10% and 20% cement replacement in mortars developed by Lee [4]. According to this current study, SM5, which possesses slightly lower compressive strength than CM0, is suggestive for applications where minor strength reduction is tolerable. On the other hand, applications with a strength requirement exceeding 30 MPa should consider utilizing SM15, as this replacement ratio brings more favorable environmental merits than SM10. Plus, SM20 might be applicable where high strength is not a concern. By considering applications according to specific strength requirements, the caron emissions caused by cement can be minimized to certain extents.

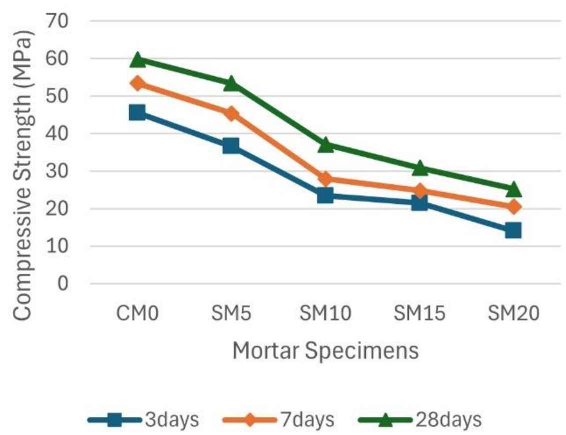

Fig. 10 Compressive strength of mortar specimens

3.4 Carbon emissions analysis

Substituting cement with an increasing quantity of wastewater treatment sludge (WWTS) exhibited a significant reduction in carbon emissions. Fig. 11 illustrates the carbon emissions of each mortar for one cubic meter volume. According to the outcomes, control mortar had the highest carbon emissions rate of 623.56 kg CO_2 per m^3, while mortar with 20% WWTS in replacement of cement attained a 19.88% decrease in carbon emissions with a value at 499.58kg CO_2 per m^3. Mortars with 5%, 10%, 15% and 20% WWTS substitutions with cement also exhibited considerable amount of carbon emissions reductions as shown in Fig. 10. Based on this analysis, adopting wastewater treatment sludge as a partial cement replacement material can be considered as an option while reducing carbon emissions in mortars to some extent.

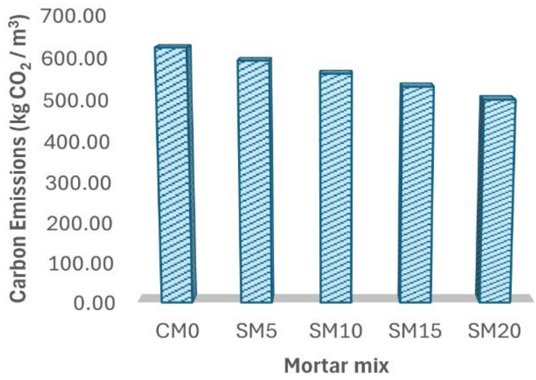

Fig. 11 Carbon dioxide (CO_2) emissions of mortars per cubic meter

4. Conclusions

This study examines the feasibility of utilizing untreated wastewater treatment sludge from the Nong Khaem water quality control plant in mortars with different cement replacement proportions to encourage sustainability in the construction industry of Thailand. Along with comparative carbon emissions analysis per volume of mortars, the physical properties of mortars were examined through flowability and setting time, as well as the mechanical performance of mortars were analyzed through compressive strength testing. From this study, the following conclusions can be drawn:

1. The utilization of untreated wastewater treatment sludge (WWTS) reduces the flowability of mortars. The higher the quantity of cement replaced by untreated WWTS, the steeper the decline in the flowability of mortars.
2. Even though the initial setting time of mortars shows a slight difference while replacing up to 10% of cement with untreated WWTS, the mortars with more than 10% of untreated WWTS incorporated as cement substitution highlights significant delays in initial setting time.
3. The compressive strength of all mortars with untreated WWTS shows no improvement compared to the control mortar. But replacing 10% or more cement with untreated WWTS in mortars has a greater impact on compressive strength reduction.
4. The comparative carbon emissions analysis of this study pinpoints the benefits of using untreated wastewater treatment sludge, which can reduce the carbon emissions without changing the volume consideration of the mortar mix. This approach not only reduces the carbon emissions of mortars but also promotes the economic aspect of mortar in volumetric quantity when it comes to large scale production.
5. The findings of this research contribute to considering the balance between mortars properties and carbon emissions caused by cement production. Moreover, this study supports an alternative option for sludge disposal of Nong Khaem water quality control plant and sustainability can be promoted significantly.

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