Solidified Water Treatment Sludge as Potential Supplementary Cementious Material in Pervious Concrete Pavers for Mitigating Heat Island Effect

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***Abstract* — Rapid urbanization is increasing impervious surfaces and urban heat. This study explores lightweight pervious concrete pavers with water treatment sludge and/or ceramic dust. Paver mixes were made with different ratios of sludge, where 10% replacement of fine aggregate with oven-dried sludge was still structurally sound and practical. While calcined sludge pavers had much higher compressive strength than the other pavers, the oven-dried sludge gave much less energy and cost inputs. Thermal testing of the pervious pavement compared to conventional concrete showed a 6°C drop in bottom-surface temperature at a top temperature of 40°C, though the effect diminished as temperature increased. These results confirm that sludge-based pervious concrete pavers effectively manage heat and retain structural and hydraulic performance for real-world applications and urban infrastructure challenges.**

I. Introduction

Rapid urbanization is growing rapidly worldwide due to industrialization, commercialization, rural to urban migration, lifestyle changes, and job opportunities. One of those changes is the use of compacted and impermeable areas. In 2010, there were 45.26×10^4 km^2 of impermeable surfaces globally, which made up 60.01% of all urban land and 0.30% of all land [1]. An increase in impermeable surfaces worsens environmental issues, increases pollutant accumulation, surface runoff, flash floods, and the Urban Heat Island (UHI) effect, and interferes with hydrological cycles, which may be worsened by climate change.

Urban settings face these pressures in the form of extreme rainfall, droughts, heat waves, and water-related disasters. The UHI effect is present and is a result of the heat-absorbing infrastructure and human activity [2]. Distinct from forests and water bodies, urban structures such as roads and buildings absorb solar radiation and then slowly re-emit the absorbed heat, causing urban temperatures to rise [3]. The urban heat island effect (UHIE) has negative consequences as it leads to increasing energy consumption, greenhouse gas emissions, deterioration in water quality, and increased health risks. The UHI was first recognized in London [4] and has been widely studied and coined UHI since then. Mitigation options have followed UHI assessments, such as increasing greenery, green roofs, cool pavements, and implementing smart growth [5].

Of these options, the first is pervious concrete, which is considered one type of cool pavement technology that aims to decrease urban temperatures through water infiltration and evaporation [6]. Pervious concrete (Figure 1) allows for water infiltration and has high porosity because it is made from little fine aggregate [7]. Pervious concrete cannot completely restore hydrology before urbanization, as it can only enhance infiltration and reduce runoff as compared to conventional concrete. Pervious concrete is slightly weaker than typical concrete; however, its permeability allows for potential stormwater management and mitigation of UHI [8].

Figure 1. Pervious concrete pavement

A key element in making pervious concrete sustainable in nature is utilizing waste by-products. In Sri Lanka, one of the major types of waste is alum sludge from water treatment plants. For example, approximately 300 m³ of dry sludge is produced every month at the Biyagama water treatment plant. Without any means of treatment to process sludge, it gets disposed of in landfills, which are then a significant concern for waste management practices. The Biyagama plant, when it sends dried sludge to contractors for disposal procedures, spends around 03 million rupees each year. Similarly, ceramic dusts produced in large volumes in tile cutting centers (e.g., Tiron Tile Cutting Center, Nawala) are incredibly abundant and not managed, which has the potential to add on as landfill waste. The excessive cutting of tiles (ceramic) uses water, making the dust damp, which makes it difficult to manage. Both of these wastes are both environmentally impactful and economically burdensome.

The prospective value of drinking water treatment sludge (DWTS) is the high silica composition which may produce amorphous silica (a reactive non crystalline phase) following calcination [11]. An X-ray diffraction (XRD) can be used for confirming the phase composition of the sample while compositional chemistry can be assessed with an X-ray fluorescence (XRF). The need to confirm the presence of amorphous silica is critical, before DWTS is used as either supplementary cementitious material or in the case with pervious concrete, as an additive

Research has examined the factors that may be altered in a mix design, such as the type and amount of water to cement ratio, the amount and type of aggregate and compaction methods [9]. Other work cited the study of simplified mix designs for local circumstances but there has been no work comparing alternate cementitious material mix designs. Aims of this study include realizing the potential use of water treatment sludge as a partial supplementary cementitious material to overcome waste disposal challenges [10] and reducing UHI by possibly partly utilizing ceramic waste dust in the production of pervious concrete a sustainable alternative for urban use [3].

II. METHODOLOGY

The methodology included the preparation and characterization of sludge and ceramic dust, followed by the design of a pervious concrete mix, casting of specimens, and evaluation of performance. In general, the workflow is illustrated in Figure 2, starting at the preparation of materials and ending at the thermal testing of pervious concrete pavements.

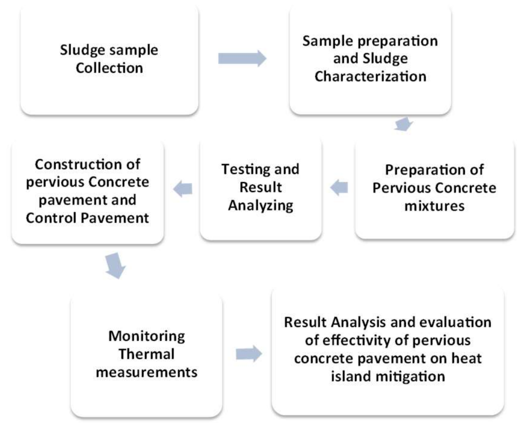

Figure 2. Sequence of methodology of the research

Sludge was two prepared in methods, one to be used as a supplementary cementitious material, the other to be used as an additive. The supplementary cementitious material sludge was prepared by drying an oven at 100 °C for 24 hours prior to crushing the dried sludge with a rubber mallet and then calcined in a muffle furnace for 2 hours at 600 °C using a heating ramp of 20 °C/min. The heating ramp was important as it not only activated pozzolanic reactivity of the sludge, but it generated amorphous silica as part of the requirement of the sludge for use as supplementary cementitious material [11]. The calcined sludge was then ground in a ball mill for 20 minutes. The fineness of the calcined sludge was checked using a 75 µm sieve. Two sludge samples were prepared for use as additives; they were dried in an oven at 100 °C and calcined at 600 °C and each sample was ground in a ball mill for one minute.

Originally wet, ceramic dust from a tile cutting facility was dried at 100 °C for 12 hours. The dried material was then passed through a screen with a 2.36 mm sieve to get a uniform particle size. The oven dried and calcined sludge samples were characterized via X-ray diffraction (XRD) for phase composition and X-ray fluorescence (XRF) for chemical composition and amorphous silica. This characterization was important to confirm the acceptance of DWTS as a supplementary cementitious material given the cementitious and silica content of DWTS.

Following the characterization, pervious concrete cubes were fabricated using the two methods described above. The mixes proportions were designed with reference to INSEE G20 concrete. Ceramic dust was incorporated into the concrete mix as 3% of the weight of the coarse aggregate because it would enhance albedo. The cube molds were 150 × 150 × 150 mm and the cylindrical mold was 100 mm in diameter and 110 mm in height. In the first method, three mixes incorporated DWTS ash at a partial cement replacement level, along with one mix without ash as a control, as was done casting a total of eleven standard cubes per mix [11].

In the second method, two mixes incorporated the use of oven-dried and calcined sludge as additives, along with one mix without additives as a control, through a total of fourteen cubes and one cylinder per mix (Kaish et al., 2021). The raw material proportions used for all of the mixes can be found in Tables 1 & 2.

TABLE 1: PROPORTIONAL RATIO OF AGGREGATES IN EACH MIX DESIGN ACCORDING TO 1ST METHOD

Mix design no	Mix Description	PCC (%)	Sludge (%)	Water (%)	Ceramic Dust (%)	Coarse aggregates (%)
1	S0C3	100	0	100	3	100
2	S10C3	90	10	100	3	100
3	S15C3	85	15	100	3	100
4	S20C3	80	20	100	3	100

TABLE 2: PROPORTIONAL RATIO OF AGGREGATES IN EACH MIX DESIGN ACCORDING TO 2ND METHOD

Mix design no	Mix Description	PCC (%)	Sludge (%)		Ceramic Dust (%)	Water (%)	Coarse aggregates (%)
			Burnt	Oven dried			
1	S0CD3	100	0	0	3	100	100
2	BS10CD3	100	10	0	3	100	100
3	OS10CD3	100	0	10	3	100	100

The cast specimens were fully tested for compressive strength, permeability, water absorption, and thermal performance.

The thermal performance testing involved placing electronic sensors at the center and edge of two concrete pavements, one control specimen and one sludge specimen. Sensors on the specimens measured the surface temperature and humidity at the bottom layer of both specimens.

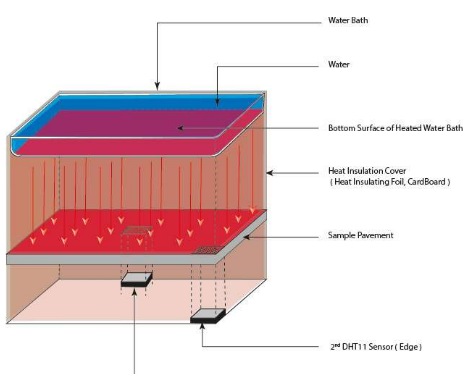

Figure 3. Cross sectional view of apparatus setup

The testing was performed in a controlled laboratory environment at INSEE with ambient temperature and wet bulb temperature of 30 °C and 28 °C, respectively, using the dry-wet thermometer to keep constant conditions over the testing period.

To assess thermal properties, we fabricated two identical wooden stands which both held a water-bath with heaters positioned above the concrete pavements. The temperature of the water bath could be monitored by the thermocouples attached to the water bath to guarantee that the top surface heat was uniform and assumed to be equal to the actual water temperature. The pavements were insulated with cardboard, and heat reflective foil was additionally used to make a one-dimensional heat transfer set-up with one-dimensional heat flow from the bottom of the water bath, through the concrete specimens. We also used cardboard insulation below the thermal sensors so that the extra heat wouldn't interfere with the thermal sensing, so we could accurately measure heat saturation throughout the pavements. Figure 3 demonstrates a section view of the overall design.

This method was a systematic evaluation of DWTS and ceramic dust incorporation into pervious concrete, and it assessed both mechanical and thermal performance. The aim was to assess acceptable mix designs for sustainable pervious concrete pavements that could lessen urban heat island effects and that offered better water infiltration by comparing control samples to samples that had sludge added but underwent the same lab conditions. The sequential process - preparation, material characterization and testing of the same materials within the same steps - one hundred percent ensured reliability and repeatability of results and provided strong results for analyzing the environmental and structural benefits of alternative forms of pervious concrete.

III. RESULTS & DISCUSSION

The characterization of water treatment sludge (WTS) was completed to help understand its potential to be used as pervious concrete material and ultimately help develop a pair of sustainable pavers. The XRD and XRF characterization confirmed that the compositions contained enough silica, alumina, and iron oxide, and the sieve analysis determined that approximately 85% of DWTS particles passed through a 75 µm sieve (similar to conventional fine aggregates). It was also observed that the particle size distribution of the DWTS when oven-dried was similar to river sand, which allowed DWTS to be a partial fine aggregate replacement. These observations have illustrated that WTS can be added to concrete mixes as a supplemental material with minimal change in material properties, and have allowed for the design of novel pervious concrete using an industrial by-product and eliminating waste material from landfills.

Mechanical performance testing provided evidence of the practical potential for using WTS in pervious concrete. In Method 1, concrete cubes made with a 10% replacement of cement by calcined sludge had the best compressive strength determination, while Method 2 (using oven-dried sludge as a fine aggregate replacement) also performed best with optimum strength at 10% replacement (the OS10CD3 mix) reaching 11.3 MPa. The OS10CD3 mix was selected for further pavement manufacturing, as it had the best overall balance of strength, ease of placement and lower energy usage when compared to calcined sludge. In conclusion, pervious concrete mixes created from WTS has the potential to meet structural performance criteria and facilitate sustainable building practices.

The hydraulic performance of the pervious concrete was also evaluated to determine its functioning will be effective in the management of rainwater runoff in urban environments. Water absorption values varied from 9–12% across all mix designs, while OS10CD3, demonstrated a water absorption rate of 9.43% consistent with typical values in pervious concrete. Permeability tested by the constant head method determined a coefficient of permeability of 0.00385 cm/s for the selected mix, which indicates that it is suitable for stormwater infiltration applications. The selected mix also identified a trade-off between strength and permeability, as increased compaction or use of finer sludge particles slightly decreased infiltration, however, OS10CD3 had sufficient porosity to allow for urban runoff management, achieving structural stability and hydrologic performance for effective dual functionality.

Thermal testing demonstrated the possibilities for pervious concrete pavers to reduce the effects of urban heat. The testing was carried out in a very controlled laboratory scenario with staged heating. The inside bottom surface of the OS10CD3 pervious slab registered approximately 6°C lower than the conventional slab at a surface temperature of 40°C. In addition to the pervious concrete cooling faster after the heat source was removed, it also demonstrated great thermal responsiveness even through the higher temperatures (60°C), cooling down somewhat slower, yet still representing clearly superior response compared to the conventional specifications. While the cooling effects were less at the higher temperature threshold, the results do support that some level of WTS / reflective ceramic dust inclusion can limit heat transfer through pervious pavements when subjected to moderate heat loads, and thus potentially contribute to the reduction of the urban heat island phenomenon.

In summary, the OS10CD3 mix, which utilized 10% oven-dried sludge as a fine aggregate replacement, provided a viable means of balancing environmental stewardship with performance effectivity in UHI mitigation. It produced acceptable compressive strength, was able to retain permeability for stormwater, and demonstrated a quantifiable reduction in surface heat transfer. This last finding demonstrates that the creative method of combining waste-derived materials to produce pervious concrete would offer a viable paver toward the dual goals of UHI mitigation and sustainable urban infrastructure. The vast variability in WTS composition and the energy expenses of calcination can limit the possibility to scale oven-dried sludge, but these challenges can be overcome with respect to policies and guidelines that promote sustainable growth practices. The combination of oven-dried sewage sludge, which is cheap and environmentally sound, brings glue to the overall pursuit of advancing pervious concrete pavements and, in turn, climate-resilient urban design.

IV. CONCLUSION

Rapid urbanization has led to an increase in impervious surfaces, which in turn has reduced stormwater infiltration, increased urban flooding, and increased the urban heat island (UHI) effect. This research explored the applicability of lightweight pervious concrete pavers that included water treatment sludge and ceramic dust, as a remedy. The study successfully developed pervious concrete pavers with sludge as a supplementary cementitious material, within the context of Jakarta, and as a reduction to UHI in urban environments.

The analysis of water treatment sludge provided important chemical and physical data to use and to implement the sludge in concrete mixes. The lightweight pervious concrete pavements were tested and provided a promise of reduced surface heat, and supports the application of pavers that can mitigate UHI in practice. The overall design, development, and testing of the work provided two summarize the work done both, reducing urban heat and re-opening/re-using waste material in a sustainable, inclusive built context.

The optimum blend replaced 10 % of the fine aggregate with oven-dried sludge, and demonstrated a reasonable level of compressive strength while lowering cost and reducing energy savings. Even though calcined sludge had the highest compressive strength, the extreme energy consumption in making calcined sludge made the oven-dried sludge the more optimal additive. The use of sludge increased the water absorbed, and therefore its durability implications will have to be considered in the design process. The thermal testing indicated that while the pervious pavement had no insulation, it reduced the bottom-surface temperature of the pavement by 6 °C compared to conventional concrete, at a temperature of 40°C. This response appears to diminish under extreme conditions, and so indicated that reflective ability has a threshold under extreme heat.

In conclusion, this study demonstrated water treatment sludge may feasibly be used as an additive in pavements. The work discussed above turned waste sludge into a value-added product, while reducing UHI effects, and enabling circular economy practices.

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