Investigating the Mechanical Performance of Concrete by Incorporating Poultry Slaughterhouse Wastewater Treatment Plant Sludge as a Partial Cement Replacement

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Investigating the mechanical performance of concrete by incorporating poultry slaughterhouse wastewater treatment plant sludge as a partial cement replacement.

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Abstract: *Poultry slaughterhouse wastewater sludge (PSWS) is a by-product of wastewater treatment, increasing with poultry meat consumption. Disposing of this waste has led to its investigation as a supplementary cementitious material in construction, due to its Calcium and Iron content. Mortar specimens were produced with 5%, 10%, and 15% sludge replacements, using both air-dried and oven-dried sludge. Compressive strength tests on 2"x2" mortar cubes determined the optimal sludge-to-cement ratio. This was applied to 4"x8" concrete cylinders, tested for compressive and split tensile strength, and 6"x6"x21" beams, assessed for flexural strength. Results showed that 5% sludge concrete had lower compressive and split tensile strength than the control mix at all ages, significantly so at 28 days. Flexural strength, however, was higher in 5% sludge specimens at 7 days but lower by 28 days. Incorporating 5% sludge in concrete reduced compressive and tensile strength but increased flexural strength, suggesting its use in non-load bearing structural elements.*

Keywords: Poultry slaughterhouse wastewater sludge (PSWS), Air-dried poultry sludge (ADPS), Oven-dried poultry sludge (ODPS), sludge-to-cement ratio, mechanical properties

1. INTRODUCTION

The utilization of waste materials in construction practices has emerged as a pivotal strategy in the field of sustainable engineering and infrastructure development. The poultry industry, a major contributor to the global food supply, generates significant quantities of wastewater during its operations [1]. Wastewater treatment is essential to mitigate environmental impacts, but it also results in the formation of byproducts known as sludge. One of the significant challenges confronting urban areas is the management of sludge due to strict landfilling regulations and the limited availability of landfill space [2]. With this, poultry slaughterhouses release substantial volumes of wastewater into the ecosystem and once treated, this wastewater produces a byproduct called poultry sludge. It contains approximately 20% total moisture content, with an average total solid content of 80%. The dry solid sludge consisted of 95% volatile solids and 5% ash. In relation, it exhibited high protein content at 62%, followed by carbohydrate content at 20%, fiber at 17%, and a fat content of approximately 1% [2]. In addition, the study also revealed that poultry sludge contains calcium at a concentration of 3.0 milligrams per kilogram (mg/kg) and iron at a concentration of 2.0 mg/kg. Both are recognized as significant constituents in cement composition. To create new eco-friendly and sustainable materials in the construction industry, the utilization of waste products has been explored by researchers.

Urban areas produce vast amounts of wastewater that must be carefully treated before being discharged into the surrounding environment. Conventional Wastewater Treatment Plants (WWTPs) primarily aim to remove pollutants from wastewater, a process that consumes significant amounts of energy from public energy distribution grids [3]. Moreover, significant quantities of sludge, the primary byproduct from wastewater treatment plants (WWTPs), are generated annually. Managing this waste incurs substantial economic and environmental costs. Reducing residues and reusing wastewater present a promising approach to fostering a circular economy and mitigating the environmental impacts linked to wastewater treatment processes [4]. In many regions in Southeast Asia, the primary disposal methods for sewage sludge are landfilling and soil conditioning. In Singapore, most dewatered sludge is landfilled at an offshore site. Recently, in Taiwan, all sewage sludge has been landfilled but plans for co-incineration and composting are underway [5]. Additionally, the substantial production of waste sludge presents an opportunity to utilize it as a renewable and reliable energy source. By harnessing energy from sludge, we can improve the sustainability of wastewater treatment processes and support a more resilient and environmentally friendly energy system [6].

In 2022, the Philippines recorded the consumption of around 1.2 billion chickens for meat production, marking significant statistics within the poultry industry. The country had been observing an upward trend in the total number of chickens processed for meat until the year 2020 [7]. The incorporation of sludge in concrete has garnered increasing attention as a sustainable practice, with sewage sludge being the predominant type utilized in prior studies [8-9]. Sludge, a byproduct of various industrial processes and wastewater treatment, contains a substantial amount of organic and inorganic materials. When properly treated and processed, sludge can be utilized as a supplementary cementitious material (SCM) in concrete production, contributing to the reduction of waste disposal costs and the conservation of natural resources [10]. This approach aligns with the principles of sustainable construction and waste management. Nevertheless, it is essential to highlight that the emphasis of previous research has primarily centered on sewage sludge, leaving poultry sludge, which serves as an alternative organic material source, relatively under-investigated within the field of concrete production.

The presence of substantial quantities of major elements like calcium and iron in both traditional cement formulations and waste products, indicates its capacity to serve as an alternative to existing construction materials. Specifically, poultry sludge, recognized for its substantial calcium and iron content, emerges as a potential candidate for substitution in cementitious materials, encompassing mortar and concrete. This prospective substitution not only holds the potential to efficiently recycle poultry waste but also capitalizes on the advantageous chemical properties of these elements to augment the performance attributes of cement-based materials.

Poultry sludge, in its entirety, has not yet received extensive exploration as a construction material within the existing body of technical literature. While some studies have examined the utilization of poultry-related byproducts, such as poultry litter or poultry ash, for specific construction applications, the comprehensive examination of poultry sludge in this context remains relatively limited. Researchers and practitioners have predominantly focused on the management, treatment, and potential agricultural uses of poultry sludge, often overlooking its potential as a construction material. Studies relating to the utilization of poultry sludge have been only explored as a renewable energy source due to its composition largely containing amounts of fats, oil, and grease, making it an excellent source for transfiguration into a biodegradable fuel [11-12]. As a result, there exists a gap in the technical literature concerning the holistic evaluation and utilization of poultry sludge in construction-related applications. Further research and investigation into the properties, processing, and engineering characteristics of poultry sludge may provide valuable insights for its potential incorporation into construction practices and materials development.

2. MATERIALS

In this study, building on the basic constituents of concrete such as cement, water, and aggregates, additional materials utilized in the study included a Digi Mortar Mixer, 2"x2" Phenolic Board Molds, Universal Testing Machine (UTM), Half Bagger Concrete Mixer, 4"x8" Cylindrical Molds, and 6"x6"x21" Flexural Beam Molds. These materials were essential for mixing, molding, and testing the concrete specimens throughout the research. The Digi Mortar Mixer ensured a consistent mix, the various molds were used for casting the specimens in different shapes and sizes, and the Universal Testing Machine measured the compressive and split tensile strengths of the concrete samples.

3. METHODS

Experimental research design was utilized due to its capacity to facilitate a controlled and methodical exploration of variables. This enabled the rigorous testing of hypotheses and the establishment of casual relations. Within the scope of this research, the approach allowed for a comprehensive examination of the influence of different poultry sludge types on various concrete properties.

3.1 Collection and Processing of Poultry Sludge

In the initial phase, the study focused on the collection and processing of poultry slaughterhouse wastewater treatment plant sludge, obtained from May Harvest Corporation in Sta. Maria, Bulacan, Philippines. The collected sludge was then subjected to two distinct processing methods: air dried and oven dried. Sludge was air-dried by spreading it on an outdoor bed, utilizing a metal pan. The drying period for this sample was 48 hours. Further reduction in water content was carried out by subjecting the sludge to thermal energy through oven-drying. To ensure that approximately 90% of its moisture content was removed, it was oven dried at a constant temperature of 100°C for 24 hours. The oven dried poultry sludge was grounded and passed through a No. 30 mesh sieve (600 µm) to ensure that any impurities were discarded.

3.2 Procedure for Processing and Testing Mortar Mixes

The study determined the mechanical performance of mortar mixes incorporating different ratios of poultry sludge as partial cement replacement. Both the fine and coarse aggregates used for this study were evaluated in terms of the following properties: moisture content, fineness modulus, specific gravity, absorption, and unit weight. Mortar mixtures were then prepared, incorporated with the sludge-to-cement ratios: 0%, 5%, 10%, and 15%. The concrete mortar mixture based on the ASTM C 109 guidelines was composed of 1 part of Portland cement to 2.75 parts of standard sand by weight. A water cement ratio of 0.485 was used for the Portland cement. The desired flow to be produced was 110 ± 5. Table 4 presented an explicit representation of the ASTM C109 mortar cement mixture, which was designated as the control mix for mortar of the study.

Table 1. ASTM C109 Mortar Cement Mixture

Component	**Number of Specimens**			
	6			
Sludge-to-Cement Ratio, %	0	5	10	15
Cement, g	500	475	450	425
Sludge, g	-	25	50	75
Sand, g	1375	1375	1375	1375
Water, mL	242	242	242	242

For the strength related properties of mortar, the mortar's compressive strength is determined through ASTM C109. This test utilized 50 mm x 50 mm cubes, which are cured and subjected to a compressive load until failure. Measurements were taken at the specified curing periods (in days): 7, 14, 21, and 28, under ambient room temperature. The maximum load produced by the machine (P) was used to determine the compressive strength (f) of the mortar specimen with the equation:

$$f = P/A \quad \text{Equation 1.}$$

Where:
f = compressive strength in MPa or psi
P = total maximum load in N or lbf
A = area of the surface in mm^2 or in^2

3.3 Incorporating Most Desirable Sludge-to-Cement Ratio in Concrete Production

Phase 3 of the study is centered on determining the most desirable sludge-to-cement ratio established from the previous phase's tests and integrating it into the production of concrete. The mix design for concrete employed in this study adheres to ACI 211.1 to ensure precision and reliability. In Table 2, a comparison is drawn between concrete mixtures for a 1 cubic meter (cu.m) volume: a control mix and another with 5% poultry sludge substitution.

Table 2. Concrete Mix Design from Calculation (1 cu.m)

Component	Control	With 5% ADPS
Water-to-cement ratio (w/c)	0.626	0.626
Cement (kg)	327.48	311.11
Poultry Sludge (kg)	-	16.37
Water (kg)	167.79	167.79
Fine Aggregate (kg)	875.96	875.96
Coarse Aggregate (kg), Max size of 19 mm	904.66	904.66

Evaluation of strength compressive strength test of the concrete samples were conducted in accordance with ASTM C39, utilizing a cylindrical mold having a size of 100 mm x 200 mm (4" x 8"), following the specification set by ASTM C31/C31M. Specimens were cured under a specific period, under an ambient room temperature. Samples were then tested through applying the load by the UTM. The displacement and Load were measured with the Handheld Data Logger TC-32K connected to a Tokyo Sokki Kenkyujo load cell. Equation 1 was then utilized to compute the compressive strength of the test samples.

As for the split tensile strength, its evaluation adheres to ASTM C496. Following the specifications mandated by ASTM C31/C31M, the concrete mix is tamped into cylindrical molds that have a diameter of 100 mm, and length of 200 mm. Specimens were cured and subjected to a vertical load, applied at a constant rate until failure is observed. Strips were placed in between the specimen and load bearing plate. The curing period for this test were set at 3, 7, and 28 days. The maximum applied load is taken into consideration in computing the tensile strength of the sample using the following equation:

$$T = \frac{2P}{\pi l d} \quad \text{Equation 2.}$$

Where**:**
T = splitting tensile strength, MPa
P = maximum applied load, N
l = length, mm
d = diameter, mm

Moreover, testing of the flexural strength of concrete were performed through ASTM C78/78M. A prismal shaped mold was utilized to cast the specimen, having dimensions of 150 mm x 150 mm x 500 mm in accordance with ASTM C31 or C192. Before conducting the test, specimens were appropriately kept moisturized to avoid any possibility of decrease in flexural strength. Support blocks were used to position the specimens in alignment with the lines perpendicular to the side faces, to guide the load's application to the beam with respect to the prescribed third-point loading configuration. The Enerpac Loadcell and hydraulic jack were utilized for the test. The specified lengths and loading lines were followed as outlined in the ASTM. Tests of the specimens were conducted at 7 and 28 days of curing. Extreme fiber stresses of the sample were between 0.9 and 1.2 MPa/min following a loading rate calculated using the equation below.

$$r = \frac{Sbd^2}{3L} \quad \text{Equation 3.}$$

Where:
r = loading rate, MN/min,
S = rate of increase in extreme fiber stress, MPa/min,
b = average width of the specimen, mm,
d = average depth of the specimen, mm, and
L = span length, mm.

The flexural strength of the samples was calculated, and the loading rate is determined using the equation below.

$$R = \frac{3PL}{2bd^2} \quad \text{Equation 4.}$$

Where:
R = modulus of rupture, MPa,
P = maximum applied load, N,
L = span length, mm,
b = average width of specimen, at the fracture, mm, and
d = average depth of specimen, at the fracture, mm.

4. RESULTS AND DISCUSSION

This section provides an analysis of mortar's compressive strength and the mechanical properties of concrete. It includes experimental data collected and compares these results with control samples. A series of graphs illustrate performance variations, followed by a detailed discussion and analysis of the findings.

4.1 Compressive Strength of Mortar

After replacing cement with poultry sludge waste material (PSWS) on the compressive strength of mortar specimens, it was observed that higher PSWS replacement resulted in lower compressive strength, regardless of drying method (air or oven drying) and curing time (7, 14, 21, or 28 days). Overall, air drying led to higher compressive strength than oven drying for all replacement percentages and curing times. The 5% cement replacement with air drying yielded the best results, with the least reduction in strength. Compared to the control group, this method saw a decrease of only about 20% in strength at 21 days curing time. Oven drying consistently resulted in lower strengths across all curing periods and replacement percentages, with reductions exceeding 40% even at the lowest 5% replacement level.

Figure 4. depicts the compressive strength of the mortar specimens at 28 days. The control sample achieved its highest compressive strength at 21.64 MPa on day 28. Air-dried specimens with 5% replacement reached 20.02 MPa, closely approaching the control. However, at 10% and 15% replacements, strengths were lower at 13.72 MPa and 8.69 MPa, decreases of approximately 37% and 60%, respectively. Oven-dried specimens showed strengths of 11.57 MPa, 7.75 MPa, and 5.36 MPa for 5%, 10%, and 15% replacements, respectively, indicating decreases of approximately 47%, 64%, and 75%. These results confirmed that extended curing improved strength, but the negative impact of oven drying, and higher cement replacement persisted. The same trend was observed for days 7, 14, and 21, as shown in Figures 1 to 3.

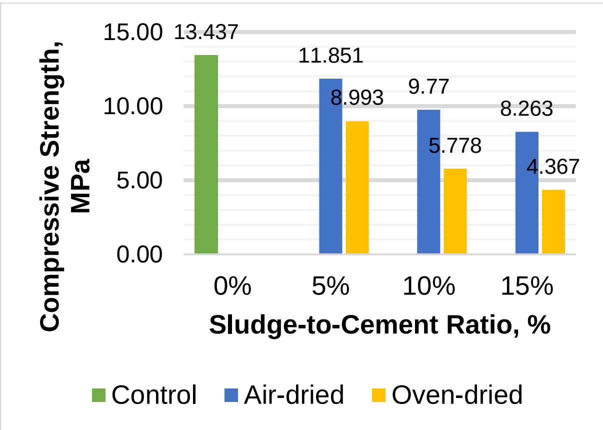

Fig. 1. Compressive Test for Mortar Specimens (7-Days Cured)

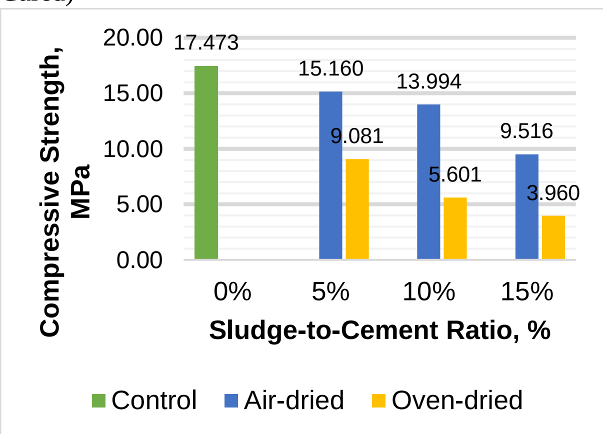

Fig. 2. Compressive Test for Mortar Specimens (14-Days Cured)

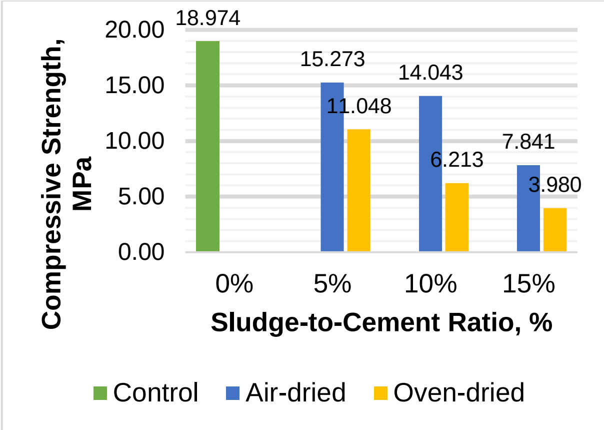

Fig. 3. Compressive Test for Mortar Specimens (21-Days Cured)

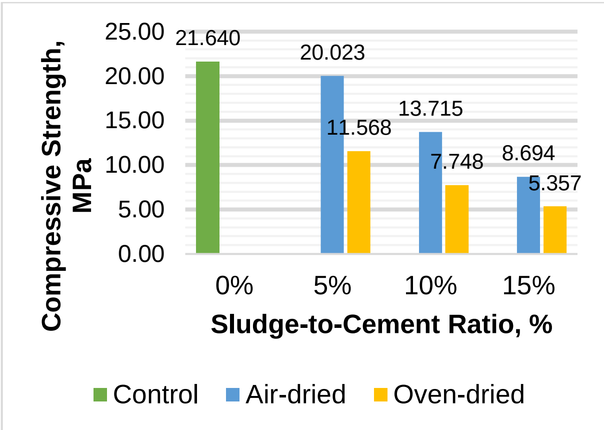

Fig. 4. Compressive Test for Mortar Specimens (28-Days Cured)

Furthermore, the experiment conducted on mortar specimens with varying levels of cement replacement using poultry sludge, an examination of compressive strengths revealed a consistent relationship between drying methods and strength outcomes. Notably, air drying consistently resulted in higher compressive strengths compared to oven drying across different replacement percentages and curing periods. This trend mirrors observations from related research, such as Grabowski et al. in 2023 [13], which explored the effects of drying techniques on mortar strength properties when incorporating sewage sludge. The strengths observed in air dried specimens suggest that the gentler drying process may mitigate internal stress and micro-cracking, thereby contributing to improved overall strength. Moreover, the results showed that while curing time enhanced compressive strength, the benefits were more pronounced with air drying and lower cement replacement levels. Oven drying consistently resulted in lower strengths across all curing periods and replacement percentages.

4.2 Evaluation of Most Desirable Sludge to Cement Ratio

After the evaluation of mortar specimens, it was determined that the desired ratio for partial replacement of cement with ADPS in concrete is 5%. The results of the tests conducted on concrete specimens at 7, 14, and 28 days are presented in this section, showing the compressive strength, split tensile strength, and flexural strength of five samples and three samples at each interval, respectively.

4.3 Compressive Strength of Concrete

In Figure 2., all the specimens in which cement content was replaced with 5% ADPS showed a reduction in compressive strength at 7, 14, and 28 days of curing, following the trend shown in the evaluation of mortar specimens despite all control samples on the 28th day of curing reached the target strength of approximately 24 MPa Therefore, showing the degrading properties of ADPS in its partial replacement. The fracture patterns of concrete cylinders during compressive strength testing at 28 days were observed in this study. Most specimens consistently exhibited Type 2 and Type 6 fracture patterns, showing the same behavior for both control and ADPS specimens. However, the compressive strength of the specimens decreases with the incorporation of ADPS, suggesting that while the fracture pattern remains consistent, the addition of sludge affects the specimens' overall strength development.

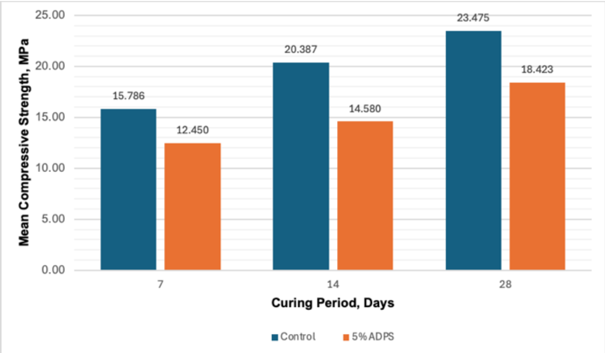

Fig. 5. Mean Compressive Strength (MPa) per Curing Period.

Ultimately, like mortar specimens tested for compressive strength, samples were consistent in terms of the increase in strength produced. Results of this evaluation are comparable to the study of Mourtada Rabie in 2016 [14], wherein a strength of 24.35 MPa was achieved at 5% replacement of oven dried sewage sludge on the 28th day of curing with a target strength of 30 MPa in its mix design.

4.4 Split-Tensile Strength of Concrete

For split tensile strength, a consistent increase in strength is observed for concrete samples containing pure cement as seen in Figure 3. However, the addition of 5% ADPS only slightly contributed to the strength of the concrete. For all curing periods, 3, 7, and 28 days the mean strengths under control were 1.891 MPa, 1.985 MPa, and 2.774 MPa, respectively. Meanwhile, an inverse trend is observed for the 3rd and 7th day curing periods, with strengths recorded at 1.526 MPa and 1.475 MPa, for its mean, respectively. For the last curing period, the mean recorded strength is 1.891 MPa. This indicates the inefficiency of PSWS for split tensile strengths.

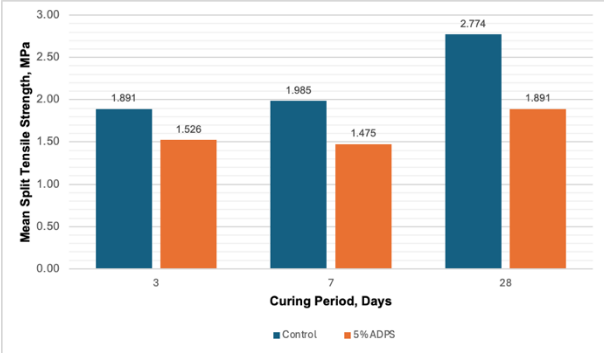

Fig. 6. Mean Split Tensile Strength (MPa) per Curing Period.

Compared to the study of Mandilik & Karale in 2018 [15], where a split tensile strength of 3.91 MPa was achieved with the utilization of sewage sludge ash incinerated at a high temperature, the current research, which is only limited to processing the sludge into ADPS, resulted in a considerably lower strength of 2.223 MPa. This shows that the method of processing sludge significantly impacts the resulting split tensile strength. Specifically, Mandalik & Karale (2018) [15] demonstrated that incinerating sludge at high temperatures can achieve greater strength. However, this study focuses on the utilization of PSWS rather than sewage sludge. Moreover, this difference highlights the importance of the incineration process in enhancing its properties.

4.5 Flexural Strength of Concrete

Specimens evaluated for flexural strength were cured for 7 and 28 days to assess their early and late strength. In accordance with ASTM C239, the modulus of rupture for the specimens were computed. This considered the linear dimensions at the fracture of each beam (in mm) and the maximum applied load (in N).

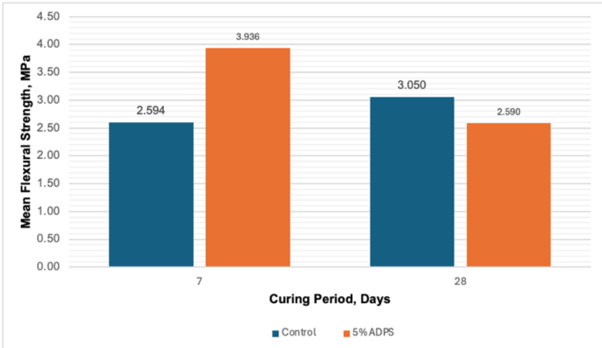

Fig. 7. Mean Flexural Strength (MPa) per Curing Period.

As seen in Figure 4, 7 and 28-day curing periods, concrete with 5% ADPS replacement at 7 days recorded the greatest flexural strength at 3.936 MPa, which exceeds that of the control sample at 28 days with 3.050 MPa as seen in Figure 5.19. This indicates the potential of ADPS in contributing to the early strength in concrete. However, at a longer curing time, prolonged exposure to water may decelerate its development, resulting in lower values than that of the concrete sample. Moreover, as stated by Irshaid in 2021 [2], the chemical components of poultry sludge contain high levels of phosphorus which may contribute to a decrease in the flexural strength of the concrete with respect to time. With the assumption that poultry sludge from wastewater treatments plants also typically contains P_2O_5 (Phosphorus Pentaoxide) similar to that of sewage sludge, the presence of this chemical may react with other components in concrete, potentially leading to its deterioration in terms of strength.

4.6 Stress-Strain Diagram for Compressive Strength of Concrete

The stress-strain diagram presented in figure 5. shows the compressive strength vs strain of 5 control concrete specimen and 5 with ADPS replacement. The average fc' of the control specimen is 23.475 MPa compared to the 18.423 MPa of the sludge specimens. This translates to a notable strength reduction of approximately 21.53% due to the incorporation of poultry sludge. Further analysis can be conducted by calculating the modulus of elasticity for both concrete groups.

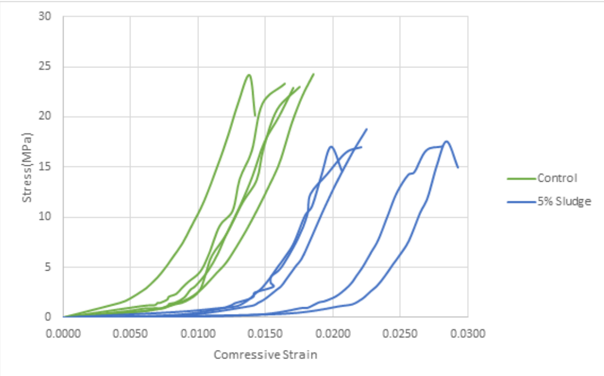

Fig. 8. Combined Stress Strain Diagram of 28 Day Cured Concrete

5 CONCLUSIONS

This study investigated the use of Poultry Sludge Wastewater Sludge (PSWS) as a partial cement replacement in concrete. Utilizing waste materials like PSWS can promote sustainability in construction by reducing reliance on natural resources and proper waste disposal. The addition of ADPS improved the workability of concrete, resulting to a greater value for slump than that of the control samples. Replacing 5% of cement with air-dried PSWS (ADPS) resulted in the optimal replacement between maintaining the mechanical properties of the concrete. Results showed that the compressive strength of the ADPS reduced by 24 % and the split tensile strength reduced by 37% compared to the control specimen with no ADPS. The flexural strength Concrete sample with PSWS and cured at 7 days can withstand the greatest amount of bending stress, among all specimens. However, with time, this decreases, indicating the waste material's degradation properties to concrete performance.

The optimal sludge-to-cement ratio was initially selected through mortar specimens of varying replacement proportions: 0%, 5%, 10%, and 15%. In accordance with ASTM C109, the mortar cubes were subjected to compressive stress. Specimens incorporated with 5% Air dried poultry sludge recorded the average compressive strength with an average percentage difference from the control samples of 14.02%, providing implications that it is the most ideal among the considered ratios.

Concrete cylinders incorporated with 5% Air dried poultry sludge (ADPS) were then evaluated in terms of compressive, split tensile, and flexural strength. 5% ADPS incorporated concrete exhibited the same behavior with regards to strength development, whereas the strength directly increases with the length of the curing period. Although, it has been deduced that the introduction of PSWS has contributed to the reduction of compressive strength. This influences the elasticity modulus derived from the stress-strain diagrams presented for all the samples. It provides implications that Poultry Slaughterhouse Wastewater Sludge (PSWS) may also contribute to lowering the specimens' resistance to deformation. This trend is similarly observed by values from the split tensile strength test, where control samples recorded greater values than that of specimens with PSWS. Under this parameter, it was also observed that a slight decrease in strength can be associated with a prolonged curing time, specifically within the 3-to-7-day period. When assessed in terms of flexural strength, it may prove to be beneficial in increasing the early strength of concrete. From the conducted test, it was recorded that the sample with PSWS and cured at 7 days can withstand the greatest amount of bending stress, among all specimens. However, with time, this eventually decreases, indicating the degradation properties of the waste material to the performance of concrete.

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