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RESEARCH

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Effect of Using Recycled E-Waste Plastic as Coarse Aggregate with Supplementary Nano-fills in Concrete

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Abstract

Last few decades have witnessed significant amount of plastic consumption due to the population growth as well as urbanization. The main goal of this research is investigating the utilization of waste plastic as an alternate for traditional natural aggregate in construction materials. To accomplish the objective of this study, seven distinct mix proportions were utilized. The mix includes control, varying percentage of plastic coarse aggregate (PA). In addition, nano-silica (NS) was utilized to partially replace the cement by weight of 5%. The different parameters of concrete including fresh and hardened state alongside stress -strain behavior, Poisson's ratio and microstructure were examined. The findings revealed that NS shows negative effect on workability but plastic aggregate in concrete exhibits enhancement in workability. However, substituting natural aggregate with plastic aggregates results in a reduction of approximately 33% in compressive strength and 34% in tensile strength. Meanwhile, the inclusion of NS enhanced the strength with modified micro structure. In conclusion, the partial substitution of natural aggregate with plastic aggregate demonstrated promising performance, underscoring its potential contribution to the advancement of sustainable concrete production.

Keywords Construction materials, Waste plastic, Nano-silica, Plastic aggregate, Thermal conductivity

1 Introduction

Concrete, which is composed of cement, sand, water, coarse aggregates, and additional inert components stands as the foremost globally employed construction material. The global average of concrete used per person has reportedly tripled over the past four decades, and with annual production soaring to nearly 30 billion tons. Projections indicate a further increase in this figure in the coming years (Monteiro et al., 2017). Both the fresh and hardened properties of cementitious composites mainly depend on the properties of aggregates, typically accommodating 60–85% of its volume (Saikia & Brito, 2014). To fulfill this need, approximately 13.12 billion tons of aggregates are used annually throughout the world (Islam & Shahjalal, 2021). Natural resources are being rapidly depleted due to the massive worldwide production of concrete, which is having significant and extensive environmental effects. The extraction of sand and gravel poses a significant challenge to sustainability in the twenty-first century (Ali et al., 2023a). To overcome this issue, several studies are being conducted world-wide to find out the possibilities of different alternative aggregates instead of natural aggregates (Allujami et al., 2022; Ullah et al., 2021). Introducing plastic-based aggregates

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in concrete offers a chance to reduce the demand of natural aggregate, subsequently reducing the cost mining and transportation. Furthermore, this approach not only minimizes the demand of natural aggregate and cost of aggregate, it also addresses the waste deposition-related issues while ensuring the minimal impact on environment.

Over the past 50 years, plastic production has significantly increased due to its widespread use in daily *E*-Walife. In the waste management chain, there exist three primary methods for managing post-consumption of plastic: recycling, incineration, and landfilling. The enormous amounts of plastic waste and their limited ability to organically decompose have a negative impact on the ecosystem. Plastics used in daily life are not fully recyclable, requiring large amounts of land for disposal (Sharma & Bansal, 2016). Several studies have investigated ways to enhance plastic recycling by incorporating it into different industrial products. Within the concrete industry, the same approach involves replacing certain amounts of the conventional aggregate with aggregates obtained from plastic waste (Ahmad et al., 2021; Albano et al., 2009; Faraj et al., 2022; Ferrotto et al., 2022; Mohammed & Hama, 2022; Rahmani et al., 2013). Furthermore, the aim is not only to minimize the harmful emissions arising from plastic waste, but also to lessen the consumption of natural resources used in the production of concrete, thereby contributing to environmental conservation. Studies have reported the preparation of plastic aggregates (PA) from crushed bottles, plastic plates, boxes, thick and thin waste plastic sheets obtained from different industrial waste products as raw materials (Khan et al., 2021). According to previous reports, an increase in the quantity of PA in concrete, leads to the reduction in workability, strength, density and modules of elasticity (Jain et al., 2021; Juki et al., 2013; Rahmani et al., 2013; Sabaa & Ravindrarajah, 1997). The partial substitution of natural aggregate by PA in the range of 20–100% reduces the density up to 50% (Herki et al., 2013; Tang et al., 2008; Wang & Meyer, 2012). A compressive strength reduction of 70% was obtained, upon the replacement of fine aggregate natural with plastic waste as fine aggregate (Jain et al., 2021; Wang & Meyer, 2012). Replacing conventional aggregate by recycled plastic aggregates (RPAs) resulted in reduction in strength of the composite (Faraj et al., 2022). A study on the usage of polyethylene terephthalate, polyethylene with a high density, and polypropylene plastics as coarse aggregates showed that no matter the type of plastic, the plastic content should not exceed 20% to fulfill the requirements for design strength (Kılıç et al., 2008). Another study indicated that crushed PET plastic bottles while mixing with concrete at the range of 1.5–4.5% of total volume as partial substitute of aggregate showed reduction in concrete properties (Assaad et al., 2022). Likewise, a reduction in compressive strength was observed with replacement of 5–20% weight by concrete; however, the addition showed better resistance to impact loading (Saxena et al., 2018).

In recent years, researchers have begun using electronic waste (*E*-waste) plastic materials as aggregate in concrete. By incorporating *E*-waste into concrete, it is possible to reduce the environmental impact of *E*-waste contamination, lower energy consumption, minimize landfill use, cut fuel costs, and decrease the self-weight of structures due to the lightweight nature of *E*-waste compared to conventional aggregates, all while reducing production costs. Previous studies indicate that adding *E*- waste in concrete reduces the mechanical property limiting the application. To avoid the strength reduction, the partial substitution of *E*- waste based aggregate in conventional concrete should not be more than 20% (Prasanna & Rao, 2014). Similar results were obtained when adding crushed *E*-waste aggregates and fly ash to concrete (Saikia & Brito, 2012), wherein 15% *E*-waste reduced compressive strength by 35%. Early research indicates that integrating nanomaterials can enhance the strength development in cementitious composites modified with *E*-waste. Nanomaterials including nano-silica are increasingly attracting attention for their role in developing innovative construction materials heir importance is evident, as they enable the production of ultra-high-strength concrete, reduce the reliance on traditional Portland cement, thereby lowering environmental pollution, and achieve the desired concrete strength in a shorter curing time (Tabish et al., 2023). Moreover, studies also show that the full strengthening potential of NS can be achieved by adjusting the morphology and size of NS, optimization of the mixing process, and the addition of surfactants (Hamada et al., 2023). The incorporation of nano-silica along with *E*-waste materials, recycled coarse aggregates in concrete enhanced the mechanical property (Danish & Ozbakkaloglu, 2023; el-Hassan et al., 2024; Hinge et al., 2024; Rezaei et al., 2023). Recently, nano-silica in concrete has been demonstrated to have a considerable pozzolan influence during the first phase, improving compressive strength (AlTawaiha et al., 2023). Alhawat et al. (Alhawat et al., 2019) found that nano-silica with a greater surface area accelerated hydration, which is attributed to the rapid formation of $H_2SiO_4^{2-}$ ions. These ions then react with Ca^{2+} ions to create C-S–H gels, which act as seeds, leading to the development of a more compact C-S–H phase. The use of alternative aggregates, such as plastic waste and nanomaterials like nano-silica, has shown promise in addressing environmental concerns while maintaining concrete's structural integrity. Despite these advances, comprehensive studies examining the combined impact of plastic waste as coarse aggregate and nano-silica as a supplementary cementitious material in pervious concrete are still limited. Therefore, this work aims to investigate the properties of concrete modified with *E*-waste aggregates and nano-silica, focusing on their potential to enhance concrete performance while contributing to sustainable construction practices.

2 Materials and Methods of Preparation

2.1 Materials and Its Mix Design

In the present investigation, 43 grade coromandel OPC cement conforming IS18/112-1989 was used as binder. The initial and final setting time of the cement was 140 and 354 min, respectively. The nano-silica (NS) by weight of 5% of cement was added to enhance the mechanical properties and the particle size of NS ranged between 15 and 20 µm. The conventional river sand conforming the requirements of IS 383-201 was used as fine aggregate. The particle size ranged between 2.36 and 4.75 mm conforming the grading zone of II. Plastic aggregate was used as the partial replacement of natural coarse aggregate, typically *E*- waste was the main source of PA production. Before mixing the *E*-waste in concrete, it needs 4 stages of process to produce the PA. The production process was followed as per the previously established protocol (Ali et al., 2021), and the production process is shown in Fig. 1. In the first stage, clay and sand particles were removed by water washing process, subsequently the cleaned *E*-wastes were broken in to small shredded particles by electric crushers in second stage. In the third stage, the crushed particles were placed in kiln and heated up to 200 °C, and the heat was maintained until all the wastes are melted. Then the colloidal state of melted plastic syrup was poured in to the water tank and allowed to cool down. The cooled plastic stone was crushed as per the required size using crusher and PA was produced in fourth stage. The materials that were used in this investigation are represented in Fig. 2.

For the preliminary investigation, physical properties of all the concrete making substances are studied and presented in Table 1. The water adsorption and specific gravity of all the aggregates were found as per IS 2386 (A. S. T. M., 2015); meanwhile, ASTM C330 (A.S.T.M. C., 2006) guidelines were followed to calculate the density of PA. The grading of the fine and coarse aggregates was done as per IS 383, and IS 2430, respectively. According to the preliminary investigation, PA exhibits 48.3% light weight when compared to natural aggregate and did not absorb any water, the mix design were shown in table-2. The texture and form of both plastic and natural coarse aggregates were analyzed using optical microscope and the results revealed that the PA having high porous with more angularity rather than natural aggregate.

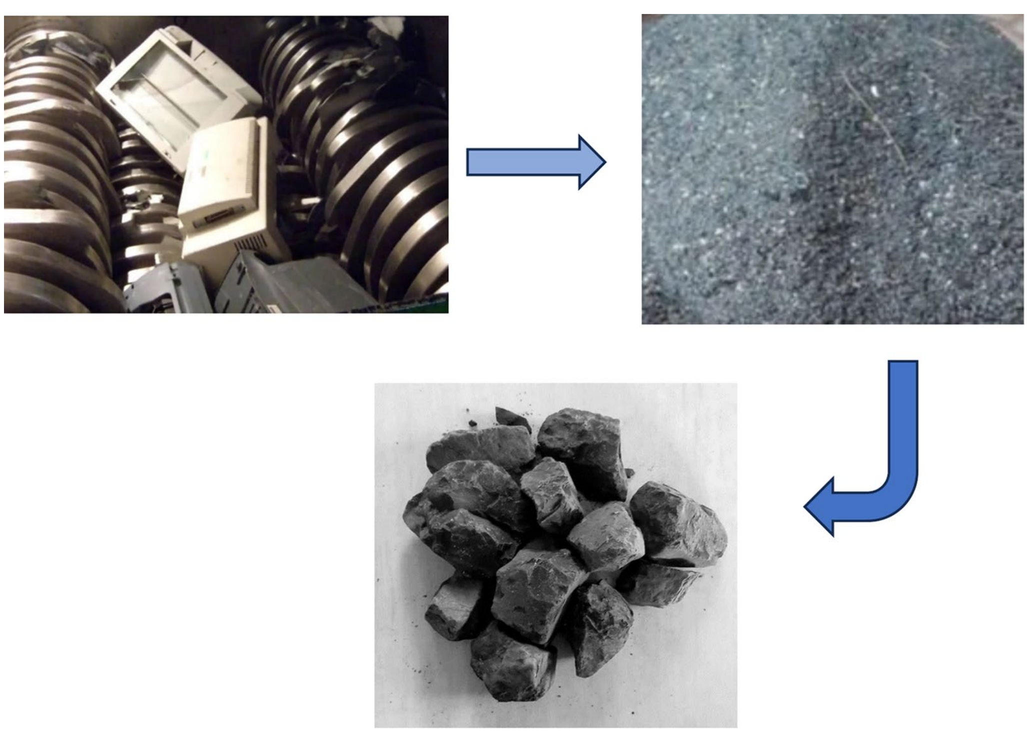

Fig. 1 Making of plastic aggregate

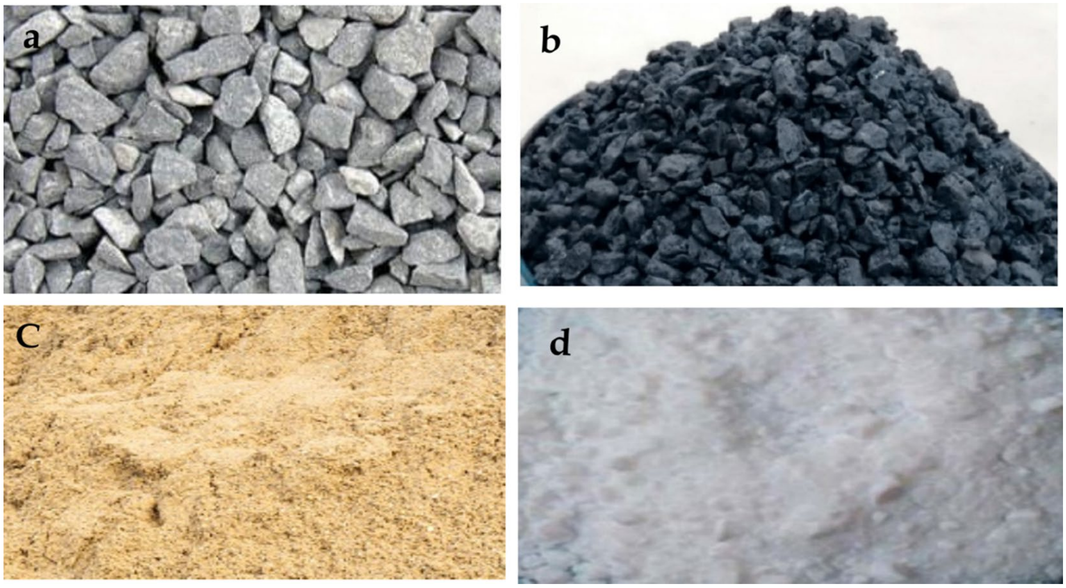

Fig. 2 **a** Natura coarse aggregate l, **b** plastic coarse aggregate, **c** natural fine aggregate, **d** nano-silica

Table 1 Specifications of materials

Characteristics	Size of the aggregate (Avg)	% of water adsorbtion	Specific gravity of aggregates	Density (bulk) (kg/m^3)	Abrasion (%)	Impact Resistance (%)
OPC	53 µm	–	3.12	1432.00	–	–
Coarse aggregate (Conv)	20 mm	0.8	2.59	1498.00	12.00	9.87
Plastic aggregate (PA)	20 mm	0.00	0.89	598.00	9.12	2.04
Sand	–	4.23	2.57	1630.00	–	–
Nano-Silica	15–20 nm	–	2.43	1582.00	–	–
Plasticizer	–	–	1.25	–	–	–

For this experimental investigation, seven different concrete mixtures were prepared with the mix ratio of 1:1.5:3 and W/C is 0.45. The first one is control mix followed by second to fourth mix are natural aggregate, which were partially replaced by 10%, 15%, and 20% of PA without the addition of supplementary filler (NS). In the remaining mixtures, cement was partially replaced by 5% of NS along with varying concentrations of PA (10%, 15% and 20%). To enhance the workability of fresh concrete 1.5% of plasticizer was added by weight of cement.

Table 2 Concrete mix design

Sample-ID	Control	10PA	15PA	20PA	10PANS	15PANS	20PANS
Cement (kg/m^3)	384.00	384.00	384.00	384.00	365.00	365.00	365.00
Sand (kg/m^3)	659.00	659.00	659.00	659.00	659.00	659.00	659.00
Natural Coarse aggregate (kg/m^3)	1286.00	1157.00	1093.00	1029.00	1157.00	1093.00	1029.00
Plastic aggregate (kg/m^3)	–	129.00	193.00	257.00	129.00	193.00	257.00
Nano-silica (NS)	–	–	–	–	19.20	19.20	19.20
Water (kg/m^3)	173.00	173.00	173.00	173.00	167.00	167.00	167.00
Plasticizer (kg/m^3)	5.76	5.76	5.76	5.76	5.48	5.48	5.48

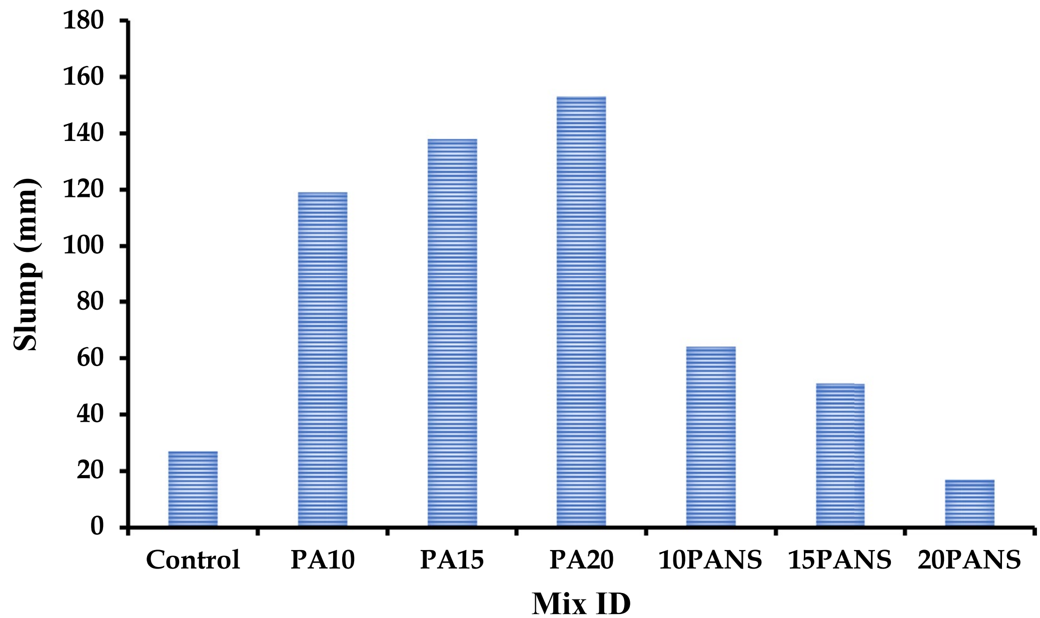

Fig. 3 Slump test results of different concrete mixers

2.2 Details of the Tests

The physical properties of fresh concrete were examined using slump and fresh density as per the experimental guidelines of ASTM C143/C143M (ASTM & C., 2007) and ASTM C138/C138M (ASTM C138 & C138M, 2017), respectively. The hardened state properties such as dry density, compressive strength, split tensile strength, modulus of elasticity, stress- strain behavior as well as lateral and longitudinal stress were examined. The dry density and split tensile strength test were conducted as per the guidelines of BS EN 12390-7 (En, 2009a) and BS EN 12390-6 (En, 2009b). The compressive strength and modulus of elasticity of concrete test were performed following by the guidelines of ASTM C39/C39M (ASTM & A., 2018) and ASTM C469 (ASTM International Committee C09 on Concrete & Concrete Aggregates, 2014). Furthermore, microstructure and morphology of both natural and PA concrete samples were analyzed using SEM and XRD analysis. The indoor and outdoor thermal performance were also studied.

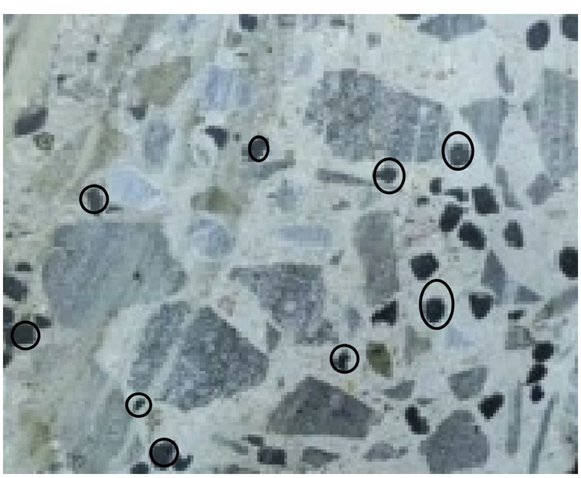

Fig. 4 Concrete specimen with plastic coarse aggregate

2.3 Preparation of Test Specimens

In this investigation, cylindrical samples size of 100 mm × 200 mm (d x h) were casted followed by the standard of BSEN 12390-6 (En, 2009b) for split tensile strength test; meanwhile, for the compressive strength test, size of 150 mm × 300 mm (d x h) was casted following the standards of ASTM C39/C39M (ASTM & A., 2018). The freshly mixed concrete samples were placed in the prepared steel moulds and compacted using table vibrator to ensure well compaction. The casted samples were covered using a plastic sheet and placed at room temperature for 24 h. Subsequently, the samples were removed from the mould and allowed to water curing for 28 days.

3 Results and Discussion

3.1 Workability

Workability is one of the crucial parameters to analyze the handling capacity as well as structural application. The slump test was used to analyze the impact of PA in concrete`s workability and the findings are shown in Fig. 3. It is to be noted that the addition of PA in concrete

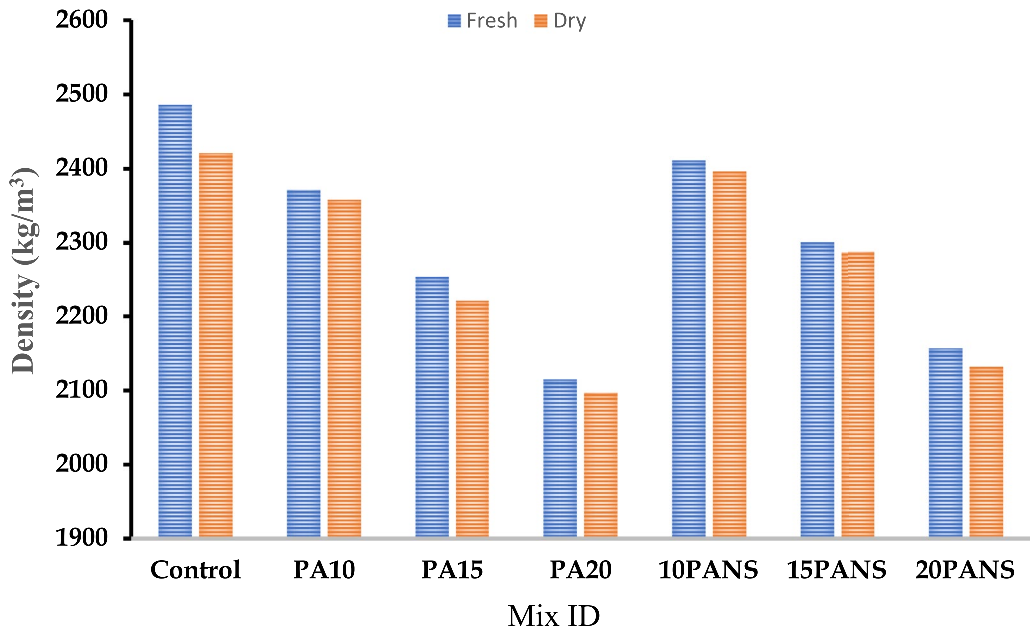

Fig. 5 Density of fresh and dry concrete specimens

increases the slum value compared to control sample. The minimum slump value of 27 mm was noted for control mix followed by 119 mm, 138 mm and 153 mm for 10%, 15% and 20% replacements, respectively. The increased slump value observed in PA blended concrete could be attributed to the hydrophilic nature, nil-water adsorption capacity and smooth texture of PA aggregates. Previous studies have also reported similar findings (Ali et al., 2023b; Ghernouti et al., 2011; Silva et al., 2013). This could be advantageous for pumping and casting of concrete over extended distances. On the other hand, the addition of NS considerably decreased the slump value of PA blended concrete mixes. The partial replacement of cement by NS 5% of weight showed maximum slump of 58 mm on 10PANS samples, followed by the minimum slump value of 17 mm for 20PANS. The drastic reduction of slump value might be because of the high surface area of NS particles leading to increase in water demand. After the completion of 28th days curing, the samples were cut in to half (Fig. 4), which did not show any evidence of segregation.

3.2 Density in Fresh and Hardened Concrete Samples

The density of fresh and hardened samples was examined and results are plotted in Fig. 5. It is evident that the partial replacement of NA by PA showed reduction in density. Meanwhile, the addition on NS showed a slight increment. However, the most significant reduction was found when 20% NA was preplaced by PA. The reduction in concrete density, which is especially noticeable when the PA content increases, might be mostly caused by substituting some of the coarse particles. Since coarse particles occupies 50–60% of total volume of concrete, their replacement probably contributes to a significant amount of the observed density reduction. On the contrary, the effect of NS (which promotes the cement hydration) on density augmentation was relatively minimal, primarily attributed to the density of NS and the degree of replacement utilized. The results are consistent with earlier studies that also observed a decrease in both fresh and dry density, when conventional aggregates were replaced with PA (Al-Manaseer & Dalal, 1997; Farahani et al., 2017; Fraj et al., 2010). This leads to the possibility of increasing the percentage of plastic particles used to make lightweight concrete, as it reduces the negative impact of plastic to environment.

3.3 Compressive Strength

The compressive strength test results of concrete samples are shown in Fig. 6. The control sample exhibited an average compressive strength of 42.32 Mpa; meanwhile, it is important to note that the partial replacement of NA by PA reduces the compressive strength with respect to the percentage of PA inclusion. The same kind of strength reduction were also recorded in previous studies (Alhawat et al., 2019; Azhdarpour et al., 2016; Babafemi et al., 2018; Mathew et al., 2013). The notable decrement was found at various percentage of replacements of PA: 10%, 15% and 20% leading to the strength reduction of 31.5%, 37.5% and 42.3%, respectively. Furthermore, the inclusion

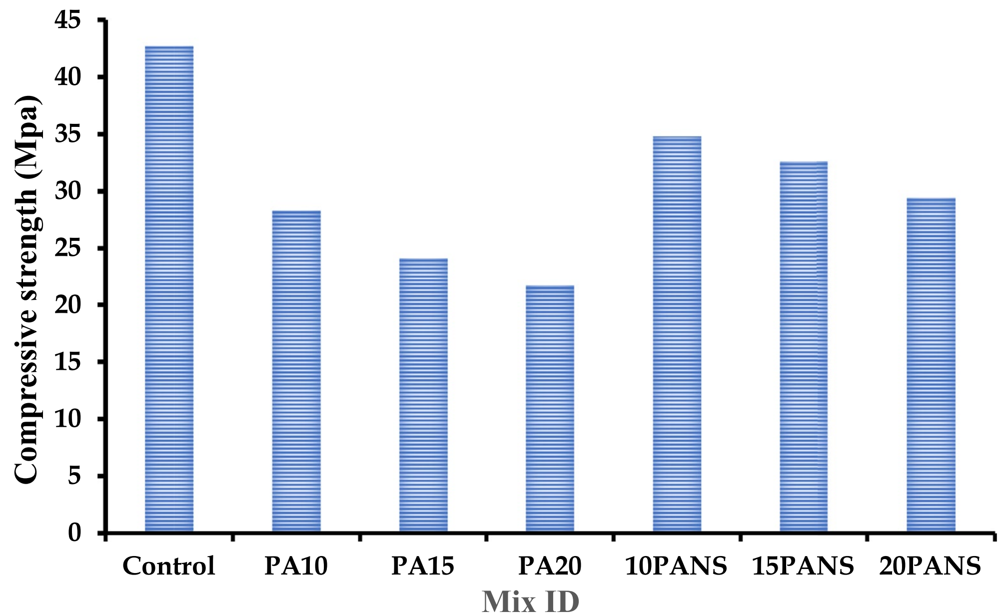

Fig. 6 Compressive strength of different concrete mix specimens

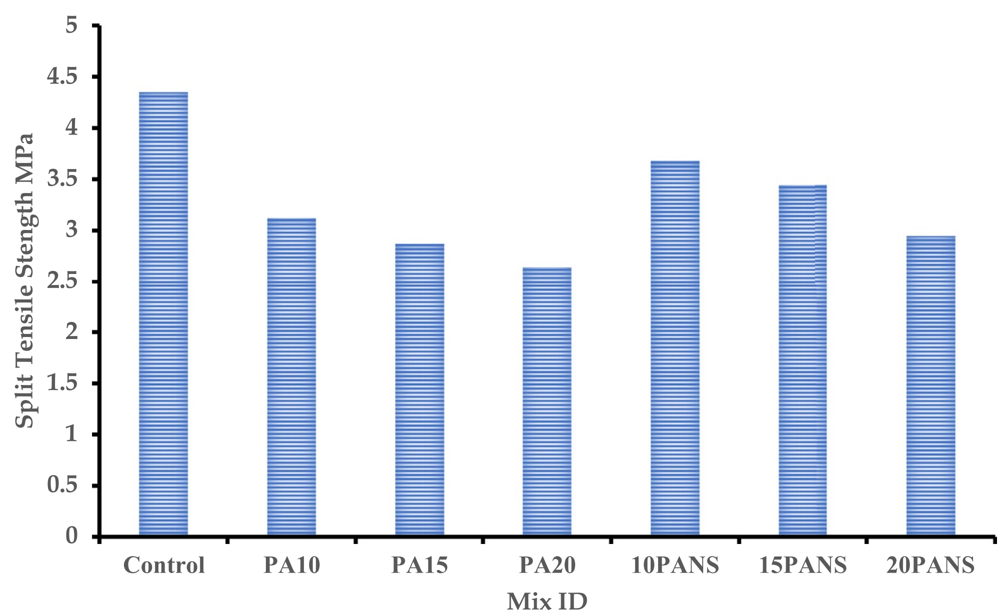

Fig. 7 Compressive strength of different concrete mix specimens

of NS with PA exhibited small amount of strength restoration. For instance, 26.5%, 28.6% and 31.5% strength reduction corresponding to the PA dosage of 10%, 15% and 20% with 5% of NS when compared to control samples were observed. At the replacement level of 20% NA by PA with 5% of NS, the strength increased from 24.5 to 29 MPa. The strength enhancement may be due to the high pozzolanic activity of NS along with their re-filling effect of pore holes. The previous studies also showed that the inclusion of NS particles in concrete accelerate the cement hydration due to its high pozzolanic activity (Islam et al., 2016; Khedr & Abou-Zeid, 1994; Nochaiya et al., 2010). Furthermore, the bond between the cement matrix and PAs are very weak due to the poor surface and high angularity. On other hand, the increasing percentage of PA in concrete leads to the water bleeding, it is because the non -water adsorbing nature of PAs with hydrophilic nature. The bleeding of water from concrete can affect the strength properties (Jansen et al., 2001). The smooth surface and presence of stagnated water in closed proximity of PA creates an unstable bond with cement matrix also affecting the strength of concrete.

3.4 Split Tensile Strength

The results of split tensile strength of all the concrete specimens are shown in Fig. 7. The control mixer exhibited the maximum split tensile strength of 4.5 MPa. Furthermore, a same trend as of compressive strength test result was observed upon increasing the PA content. It was observed that the replacement levels of 10%, 15% and 20% NA by PA exhibited the split tensile strength reduction of 32%, 33.1% and 37%, respectively, without the supplementary filler of NS. On other hand, when the NS particles were blended with PA in concrete, a corresponding reduction of 24.1%, 25.6% and 32.3%, respectively, was observed. It is evidenced that the addition of NS particles restores the split tensile strength. For instance, the split tensile strength increased from 2.86 to 3.05 MPa when NS were added with 20% PA blended concrete mix. The reduction in split tensile strength without supplementary filler might be due to the smooth surface of PA with its hydrophilic, non-water adsorption nature, and spherical shape, which makes a weaker bond between aggregate and cement. In addition, the weakened interfacial transition zone (ITZ) in the concrete also contributed towards the reduction in split tensile strength, which was similar to the reduction in compressive strength. Meanwhile, the strength restoration may be due to the re-filling effect of NS particle and strong ITZ due to the high pozzolanic activity.

3.5 E Value of Concrete Samples

The *E* value, commonly referred to as the modulus of elasticity or young's modulus, is one of the most important parameters of hardened concrete, which is influenced by quality of aggregate, compaction and strength of ITZ. Figure 8 shows the *E* value of all the concrete mixtures. Secant slope method is the most common method was used to determine the *E* value of concrete. It is calculated by drawing a slope line to the starting point of stress–strain graph and connecting the curve at the point of intersect and calculating the secant modulus as well as *E* value. The calculated *E* value of control sample (22.2 GPa) showed a noticeable decrement upon partial replacement of NA by PA as well the inclusion of supplementary filler of NS. The partial replacement of NA by PA shows the *E* value reduction of 3.94%, 11.76%, and 20.28%; on other hand, the inclusion of NS also showed a reduction of 7.2%, 25.6% and 34.2%, corresponding to the replacement of NA by PA of 10%, 15% and 20%, respectively. Jansen et al. (Liu et al., 2015) confirmed an inverse relation between stiffness and *E* value when PA content was added in concrete. The highest reduction of *E* value (203.3%) was noted when 20% NA was replaced by PA. This decreasing trend indicates deteriorated interaction between cement particles and pozzolanic activity of NS leading to reduction in modulus of elasticity. In addition, elastic modulus of concrete had significant impact upon increasing the PA substitution rather than the rigid

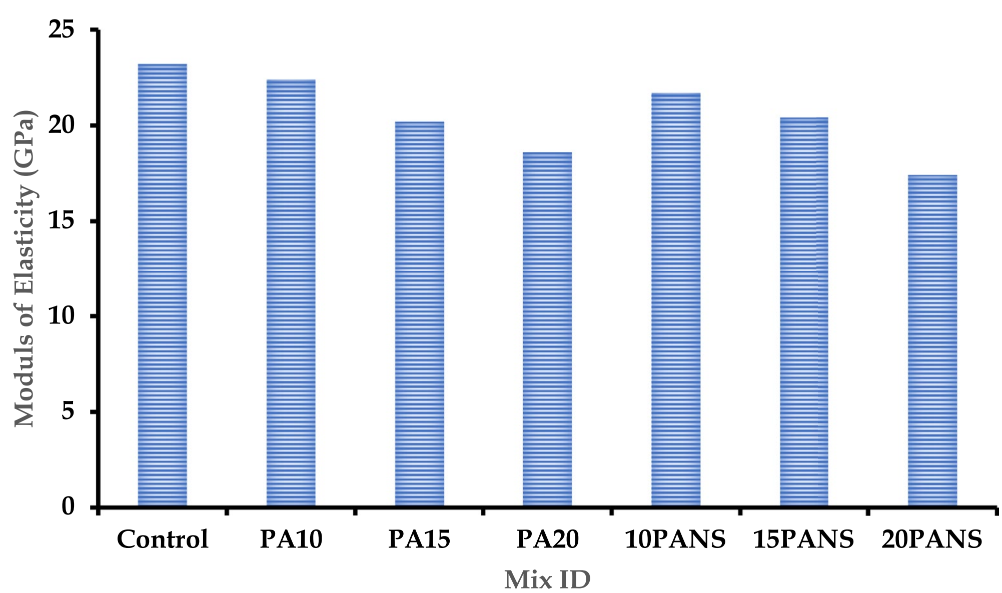

Fig. 8 Elastic modulus of different concrete mix specimens

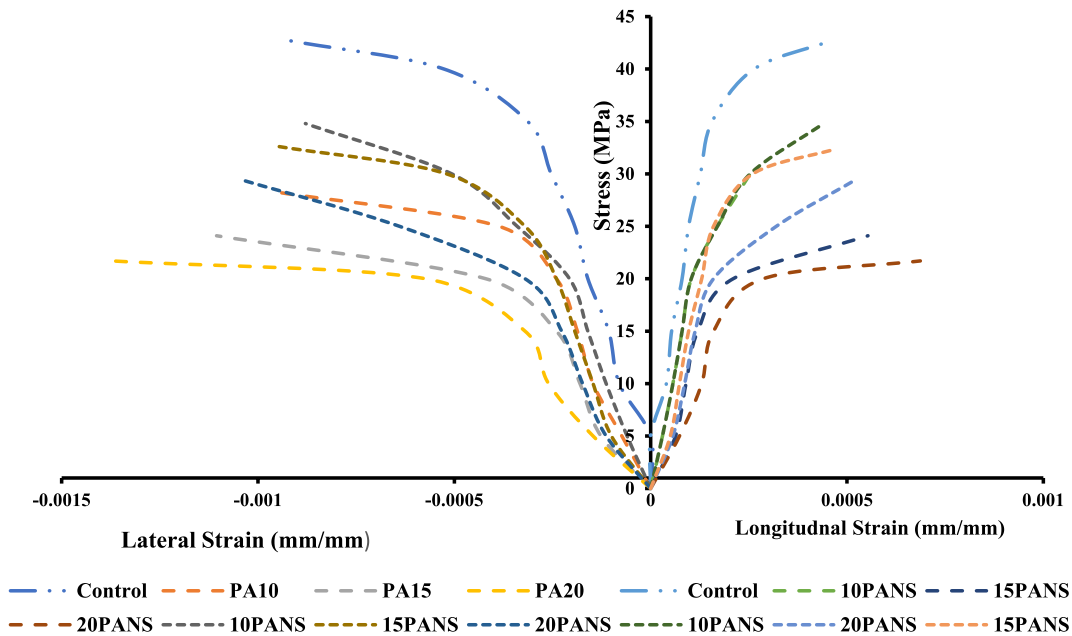

Fig. 9 Stress–strain relationship of different concrete mix specimens

natural aggregate resulting in reduction in modulus of elasticity (Fig. 9).

3.6 Relationship Between Stress and Strain

Performance of stress- strain is also the one of the crucial parameters to ensure the quality of concrete. An LVDT with a 50 mm gauge length was used to measure longitudinal strain. The lateral strain was used to measure delta rosette placed at the transverse direction of the cylindrical specimen. As the PA replacement ratio increased, there was a noticeable decrease in peak strength and the slope of the curve, with an increase in corresponding strain shown in (Fig. 9). While compared to concrete with natural aggregates, PA blended concrete's ductility was slightly enhanced, corroborating with the previous reports (Jansen et al., 2001). Higher ductility was found when incorporating the light weight aggregate in high percentage in concrete, which is also in consistent with prior investigations (Ali et al., 2021; Babu et al., 2005). In addition, it was found that the concrete fails with low strain value with high strength. The failure of increased percentage substitution of light weight polystyrene aggregate was due to high ductility compared to control sample. The unique feature of reduced brittleness was found in PA blended concrete, which was not found in conventional concrete. For the dynamic loading condition, this kind of concretes are more stable to avoid the failure.

3.7 Longitudinal Strain Versus Lateral Strain and Poisson Ratio

Figure 10 shows the lateral versus longitudinal strain of the concrete specimens with and without PA. It can be noted that similar response of lateral to longitudinal strain was observed when concrete was mixed with different substitution levels of control sample. As the concentration of PA was increased lateral strain also increased (Fig. 10). On other hand, the growth rate of lateral strain also slowly increased with the partial substitution of PA compared to control mix. It is also observed that for the specimen with high substitution of PA content, the transition between the curve starts earlier. The lateral strain increases rapidly, prompting changes in the transition point when the specimen contained PA and NS. A smooth lateral strain transmission curve was observed when adding PA in concrete indicating the reduction in brittleness of concrete. The similar effect was also found on Poisson's ratio upon adding PA and NS in concrete, as shown in Fig. 11. However, the combination of PA and NS mixed samples showed high Poisson's ratio compared to concrete containing PA alone.

3.8 Relationship Between Compressive and Tensile Strengths

The split tensile strength against given compressive strength was calculated using Eq. 1 when the concrete is less than 50 MPa. By using Eqs. 2 and 3, the maximum and minimum values of split tensile strength were calculated. Euro code -2 (Kou et al., 2009) was used to find

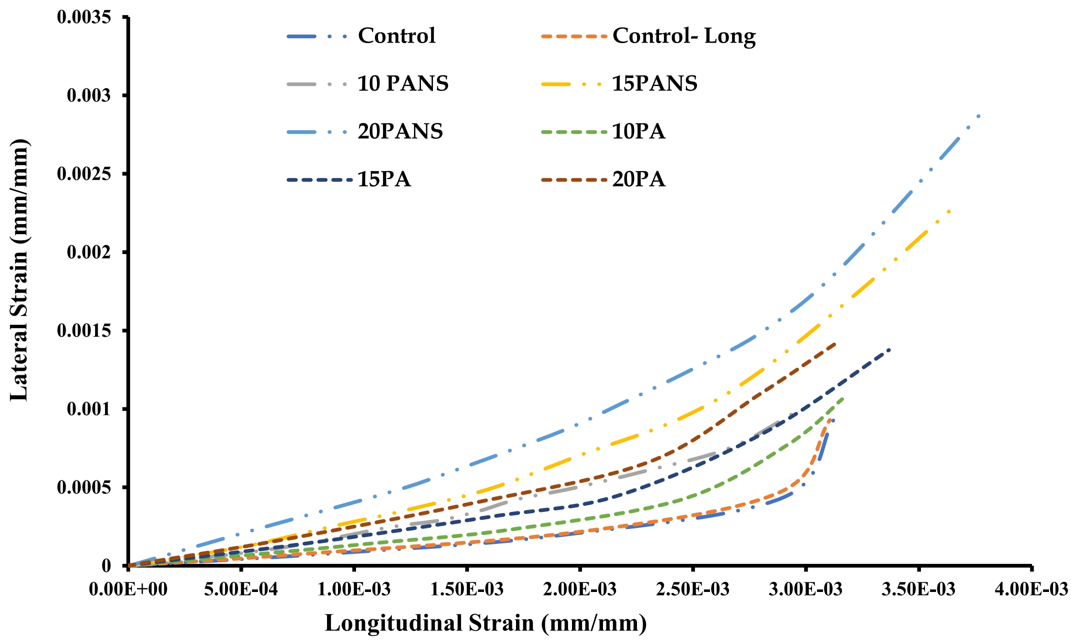

Fig. 10 Comparisons of lateral strain with longitudinal strain

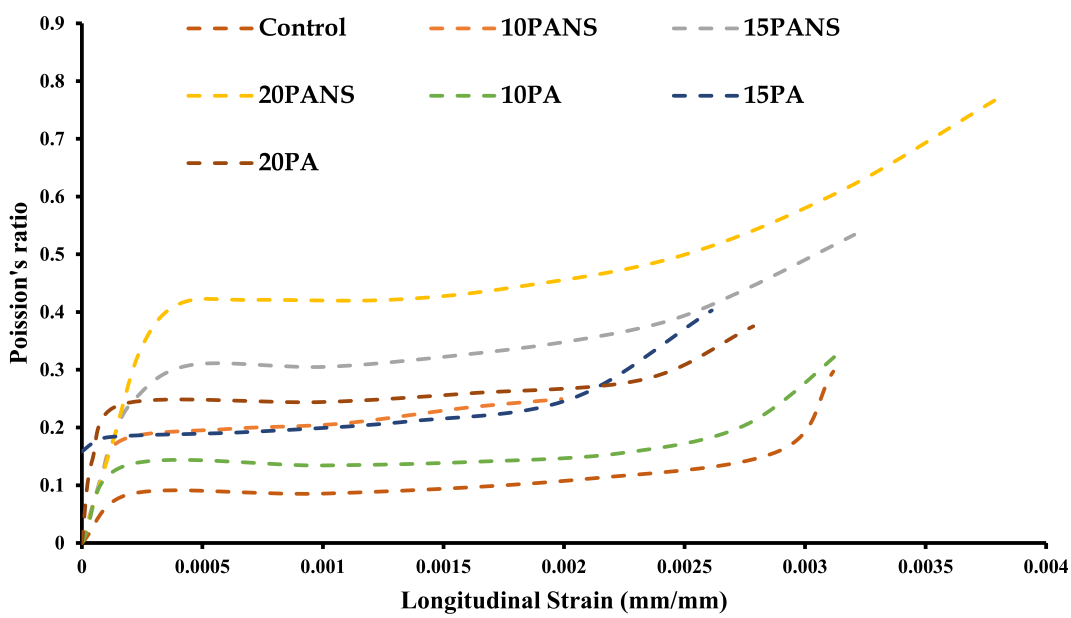

Fig. 11 Poisson's ratio versus longitudinal strain

the split tensile strength with and without PA, where f_t, f_{tm}, ft_{min}, and ft_{max} represent split tensile strength and f_{cm} stands for compressive strength:

$$f_{tm} = 0.3(f_{cm})^{2/3} \quad (1)$$

$$f_{t,min} = 0.7(f_{tm}) \quad (2)$$

$$f_{t,max} = 1.3(f_{tm}) \quad (3)$$

Split tensile strength of minimum and maximum values of the current experimental study along with previous studies (Almeshal et al., 2020; Choi et al., 2005; Kou et al., 2009) with PA coarse aggregate substitution are presented in Fig. 12. The previous studies also indicate that the values fall in the same range irrespective of the origin

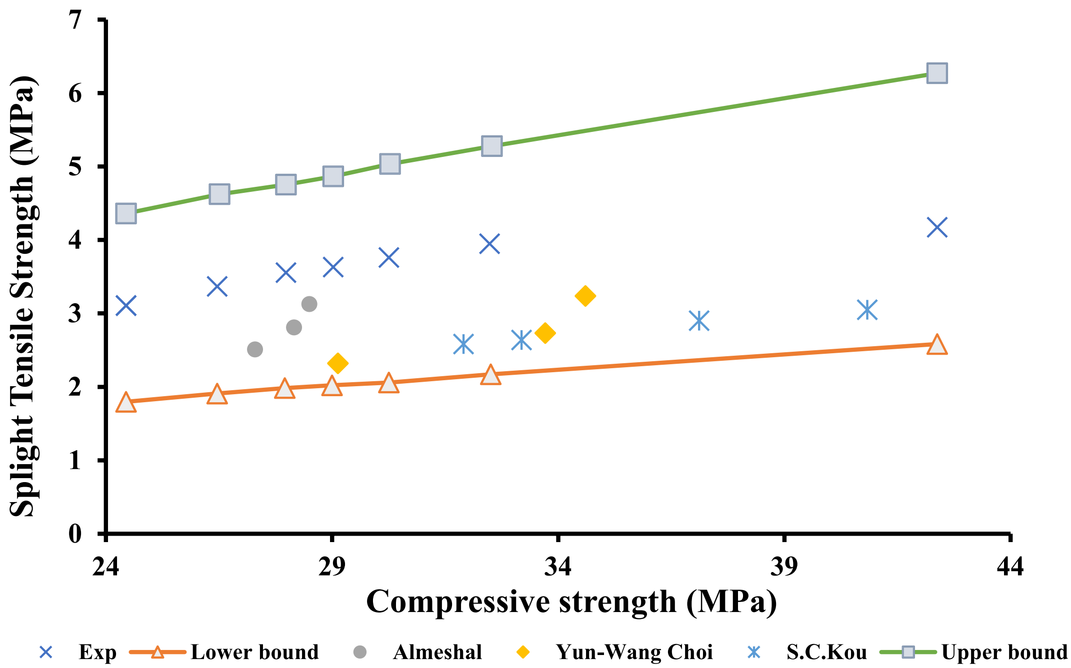

Fig. 12 Relationship between compressive and tensile strengths with different literatures

of plastic, addition of nano-fillers and water-cement ratio. Tensile strength values were calculated using equations derived from different building codes and previous research, as shown in Table 3 and Fig. 13. It is noted that, the proposed expressions values are within the range of minimum and maximum of Eurocode alongside Neville's expression (British Standard Institution 2005: General Rules & Rules for Buildings, 2005) at the base and Juki et al.'s (2013) at the upper side. Eurocode provides correction factors for computing the tensile strength of lightweight aggregate concrete, demonstrating a reduction in tensile strength with a constant compressive strength value. The experimental findings of the current study showed that the tensile strength values exceed the control concrete values estimated from Eq. (1). The tensile strength was under estimated value in the range

Table 3 Formulas from different codes and published works to calculate the split tensile strength from compressive strength

Mix Samples		Control sample	10-PA	15-PA	20-PA	10-PANS	15-PANS	20-PANS
This experiment	f_c (Mpa)	43.26	30.90	19.95	28.74	26.95	25.44	24.36
	f_t (Mpa)	4.26	3.84	3.63	3.52	3.42	3.38	3.19
ft (MPa) predicted	Juki et al	2.81	2.46	2.35	2.26	2.19	2.08	1.92
	ACI 318–11	3.64	3.19	3.08	3.02	2.96	2.88	2.77
	Neville	2.83	2.37	2.26	2.19	2.14	2.06	1.96
	Euro	3.58	3.16	2.85	2.76	2.90	2.87	2.63
	NZS 3101–2006	2.79	2.43	2.38	2.27	2.45	2.35	2.09
	IIS456	3.89	3.53	3.29	3.31	3.27	3.08	2.86
	Oluokun et al	3.89	3.25	3.09	3.00	2.93	2.82	2.67
Ratio of experiment and prediction value (MPa)	Juki et al	1.57	1.55	1.54	1.62	1.63	1.65	1.5
	ACI 318–11	1.06	1.19	1.23	1.22	1.21	1.16	1.09
	Neville	1.35	1.58	1.61	1.69	1.70	1.71	1.58
	Euro	1.13	1.27	1.27	1.27	1.27	1.25	1.21
	NZS 3101–2006	1.39	1.61	1.59	1.59	1.49	1.38	1.36
	IS456	1.17	1.14	1.12	1.12	1.11	1.08	1.03
	Oluokun et al	1.06	1.31	1.32	1.32	1.32	1.19	1.14

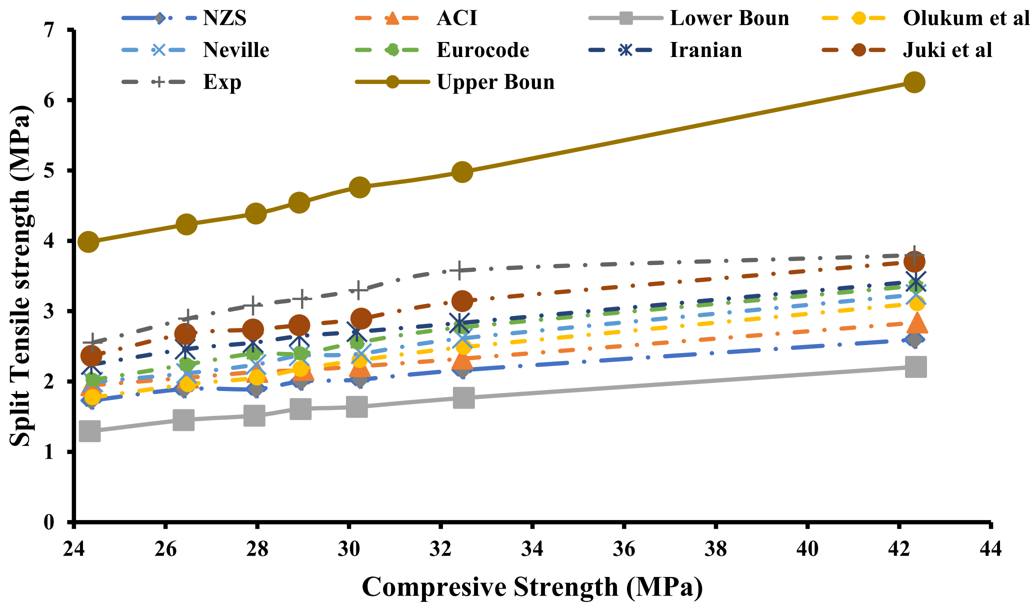

Fig. 13 Relationship between projected tensile strength versus compressive strength with different literatures

of 20–32% while using New Zealand Standard (NZS: 3101:2006) and Neville equations (Neville & Brooks, 1987). Meanwhile, using (IS 456 2000) Euro code, ACI 318-11 (CODE & A., 2022), Oluokun et al. (1991) and Juki et al. (Wang & Meyer, 2012) showed higher strength of around 13%. Table 4 shows the experimental-to-projected ratio and predicted tensile strength.

3.9 Examination at the Microscopic Level

The visual inspection of both natural and plastic aggregate was done manually. It was found that both are quite similar in size, while natural aggregate exhibited dark blue color with high density, plastic aggregate exhibited dark gray color with low density. The microscopic inspection shows that PA have spherical shape with large number of pores. Figure 14a, b shows the visual image of natural and plastic aggregates, respectively. The concrete specimen of PA with NS filler is shown in Fig. 14c, which indicates the even distribution of PA. The representative images of samples that were sliced with diamond cutter on running water is presented in Fig. 14d, which also shows the even distribution of PA in concrete mix, while no evidence for segregation was observed.

Scanning electron microscope (SEM) was used to study morphology of all the concrete samples used in this study. The SEM image of Control sample, 20PA and 20PANS are shown in Fig. 15a–c, respectively. It is noted that the control specimen exhibits crack width ranging from 1 to 5 µm with large number of pore holes of different diameter. The PA substitution in concrete enhances the crack width at the range of 5–13 µm. It is also found the pore hole diameter is larger when compared to the control mix. It may due to the low density of PA compared to NA, which affects the compaction factor. Meanwhile, the hydrophobic nature of PA makes a layer between cement paste and aggregates leading to the formation of weaker zone, promoting the crack formation. It is evident that the increased crack width and pore size were also one of the factors that leads to strength reduction. On the other hand, the inclusion of NS in concrete with PA substitution enhances the microstructure. The crack width (3–6 µm) was reduced compared to PA alone samples, while some of the pores are re-filled with a small ring shape above the pores. It is due to the reactive silica present in the NS, which enhanced the cement hydration and made strong bond between

Table 4 Weight reduction observed during TGA

Applied heat °C	0–199 (%)	200–299 (%)	300–499 (%)	500–599 (%)	600–699 (%)	700–800 (%)
Control Specimen	1.39	1.86	3.32	5.14	9.38	23.42
M20PAS	0.52	2.61	78.42	82.66	84.57	86.30

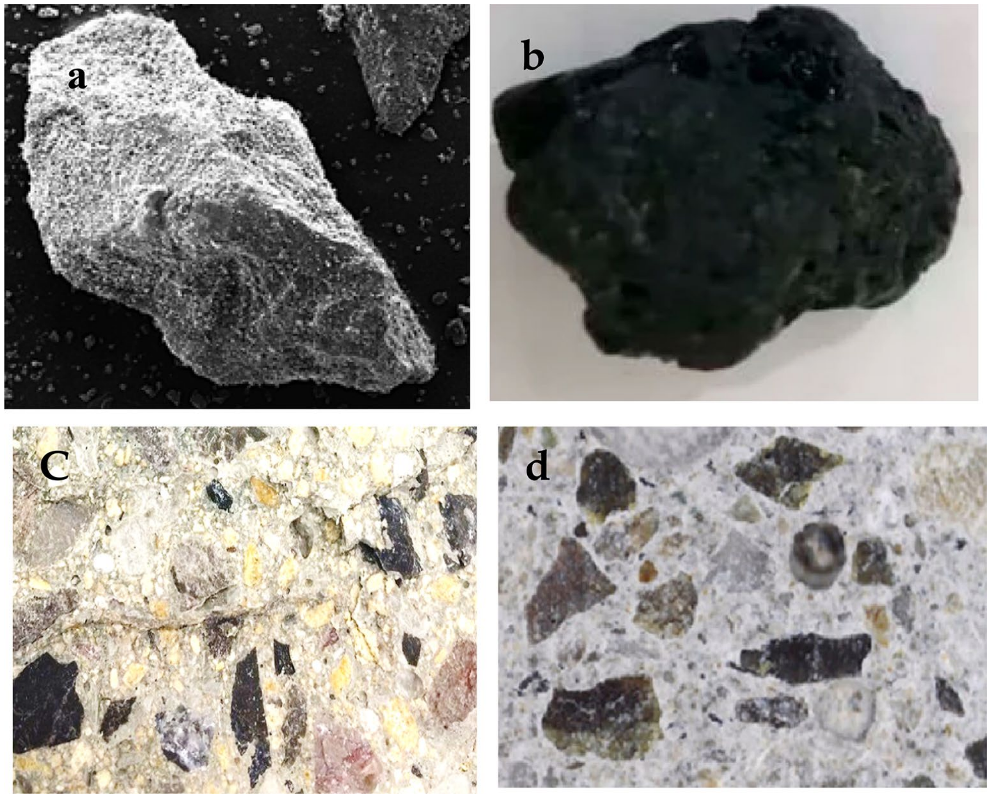

Fig. 14 **a** Visual image of natural aggregate, **b** visual image of plastic aggregate, **c** broken image of plastic aggregate concrete specimen, **d** sliced image of plastic aggregate concrete specimen

the cement matrix leading to strength enhancement. Meanwhile, excess nano-particle acted as filler materials to fill the pores. The PA samples were examined by XRD analyses, which revealed the presence of aluminum oxide and silver carbonate (Ag_2CO3), which are used as filler material in making plastics and a main ingredient while producing the plastics based microelectronic products, respectively. In addition, silver, small amount of FeO, Fe and CaO were also found in the PA aggregate (Fig. 16).

4 Analysis of Thermal Performance

Energy conservation is an important concern in the field of construction sector, especially in the building industry focusing on using energy efficient materials to minimize the energy preservation. The thermal performance of both aggregate samples was analyzed in both indoor and outdoor conditions. The present experiment used a similar test setup as the previous research carried out by the authors of Ali et al. (2021), as shown in Fig. 17. The Control and 20PANS concrete slab of size 210 mm × 210 mm × 30 mm were casted using the same mix design for this purpose. The aim of this experiment is to examine the minimum and maximum temperature difference of concrete with natural aggregate and maximum PA content with NS.

4.1 Thermal Efficiency—Indoor

The test setup shown in Fig. 17 was used to examine the indoor thermal performance, which has upper and lower chamber made with wood, whereas the sides are covered by aluminums foil to minimize the heat loss. The slab specimen was placed between the two chambers. A 250 W electric coil was placed at the upper chamber, with the help of sensors at the top and bottom, lower chamber temperature was measured. This experiment begins with room temperature and with the upper chamber temperature at 120 °C. Subsequently, the electric coil was turned off and then cooled until it reaches the room temperature (Fig. 17-a)(The obtained thermal graph of both the specimens are presented in Fig. 18. The temperature difference between the two samples indicates that both concrete specimens have different thermal conductivity. From the thermal graph, it was also noted that the increasing temperature of both upper and lower side of concrete specimens follow the same trend, while the plateau region has different trend for temperature loss. The

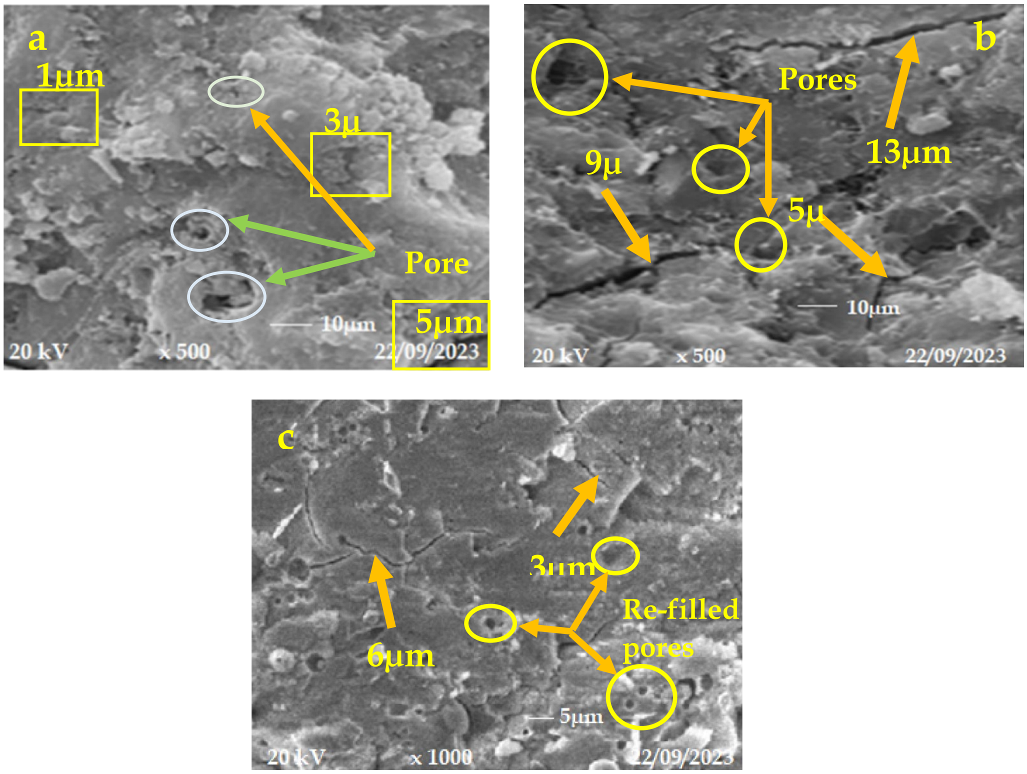

Fig. 15 **a** Crack width of cement matrix in conventional aggregate, **b** crack width of cement matrix in plastic aggregate, **c** crack width of in plastic aggregate with nano-silica

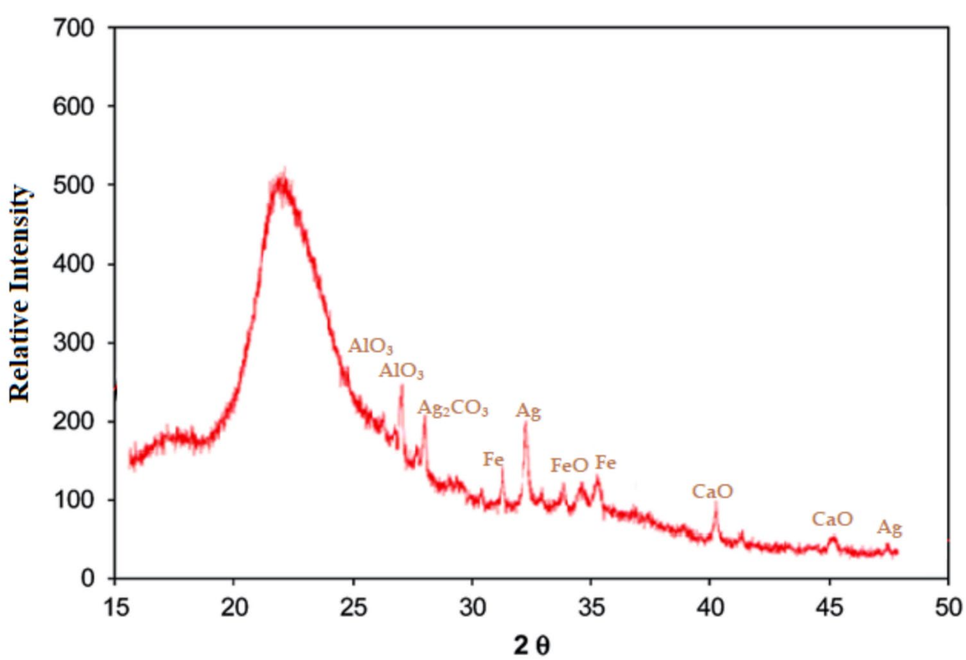

Fig. 16 XRD hump of plastic aggregate

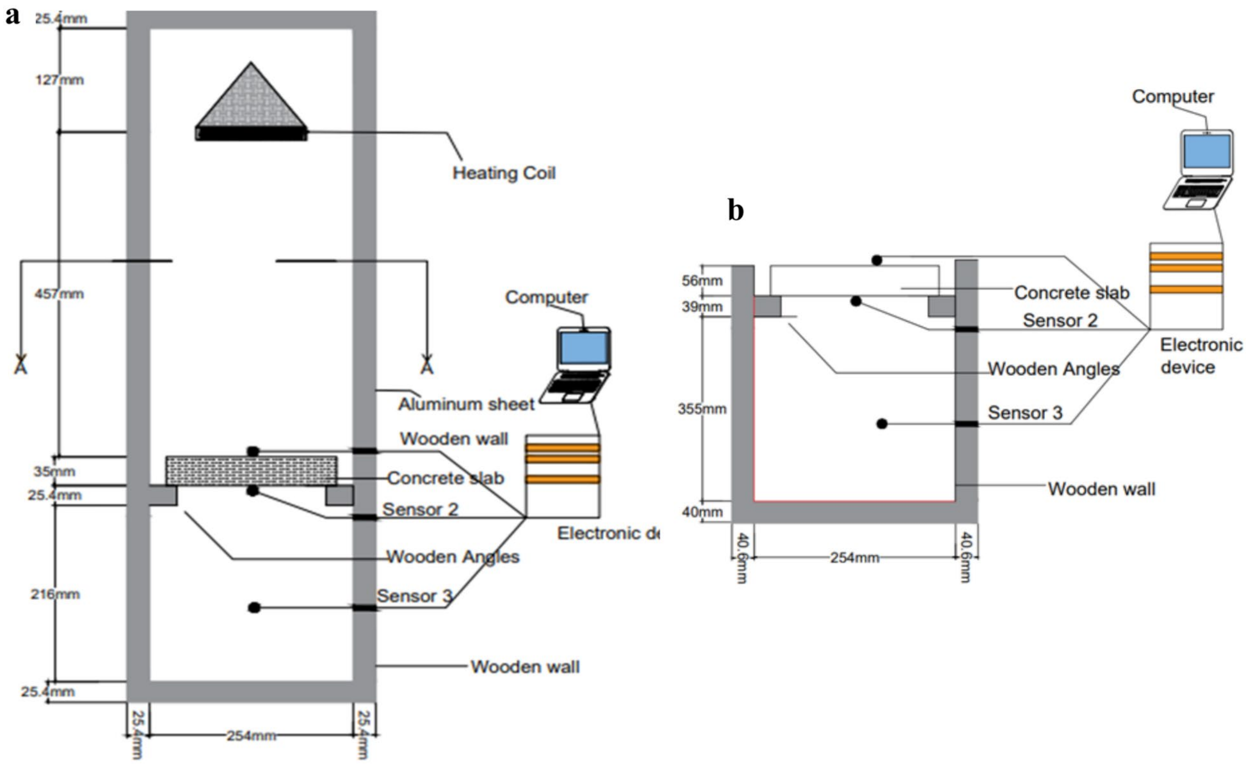

Fig. 17 Thermal efficiency test setup. **a** In-door. **b** Out-door

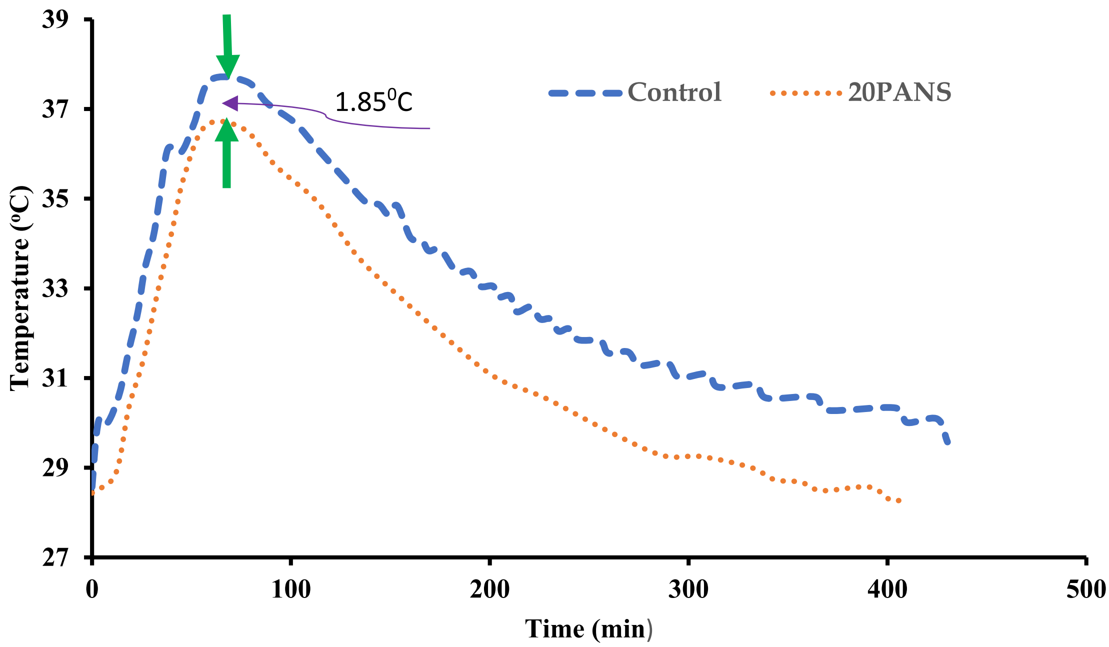

Fig. 18 Thermal performance of the specimen—indoor

concrete with partial substitution of PA with NS shows better performance rather than control sample, exhibiting 1.83 °C lower temperature at the base. Moreover, the space between the two curves were found to be increasing, which indicate that the control sample takes more

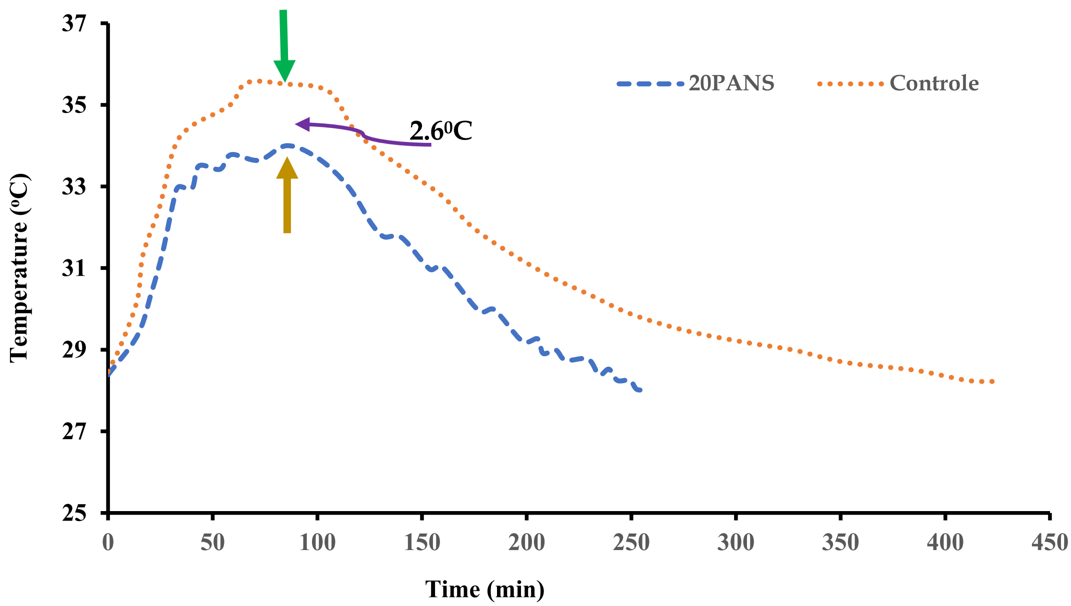

Fig. 19 Thermal performance of the specimen—out-door

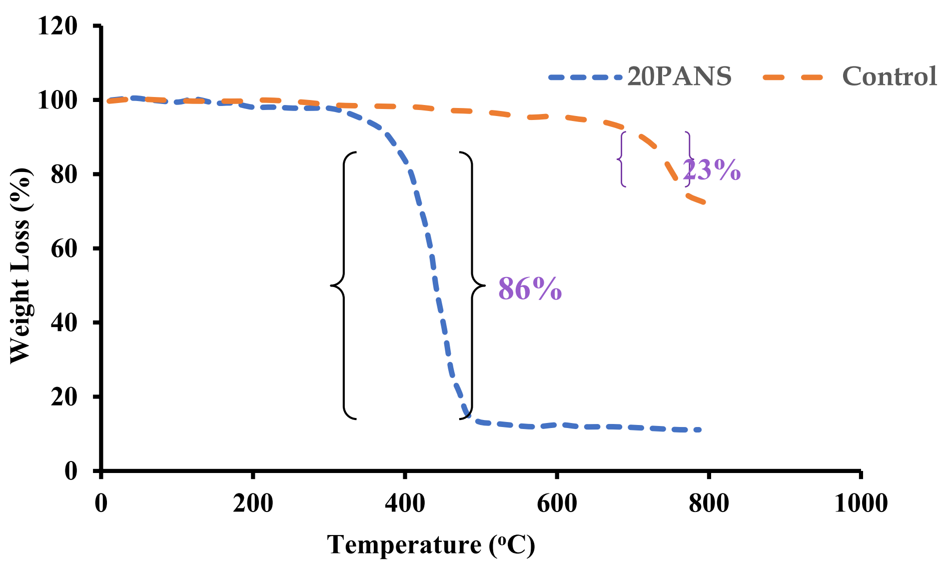

Fig. 20 Results from thermo-gravimetric study

time to achieve the room temperature rather than PA blended samples.

4.2 Thermal Efficiency—Outdoor

The out-door thermal performance of both concrete samples was studied using the following test setup, as shown in Fig. 17-b. The specimens were placed at the top of wooden box, which has only lower chamber and the dimensions are given in the figure. The thermal sensors were attached inside and outside of the slab samples connected with the thermal monitoring system, and the temperature variations were recorded at every interval, with sunlight being used as the source heat. Outdoor thermal performance of both samples is presented in Fig. 19. From the figure, it could be observed that both indoor and outdoor performance are quite similar at the increasing temperature stage. The partial substitution of PA with NS samples exhibited 11.24% low temperature at bottom surface of the slab when compared to control sample. Meanwhile, the descending curve indicates that the concrete with PA and NS shows faster cooling rate rather than control concrete. It could be because the natural granite aggregates have high specific heat adsorption rather than PA aggregates, meanwhile, liberating the heat slowly, hence taking more time to cool down. The control concrete takes around 42% more time when compared to PA blends with NS samples. From this experiment, it could be observed that both indoor and outdoor thermal performance of PA blends with NS shows better energy efficiency rather than conventional aggregate, and making it as an alternative energy efficient building material.

4.3 Thermo-Gravimetric Analysis (TGA)

Thermo-gravimetric analysis (TGA) was used to analyze the performance of control and 20%PA with NS. The samples were collected from middle core of the casted samples, and powdered in to a particle size of 50 micron. The weight of the test samples was weighed using waying scale before placing in the furnace, the temperature was progressively increased up to 800 °C and % of weight loss in the specimen was recorded first at 199 °C followed by recording at each 100 °C interval. The results showed that at 1st and 2nd stage up to 299 °C, weight loss of both samples were quite similar, which might be due to the evaporation of C-S–H, ettringites, carbo-aluminates and other hydrates. However, in the 3rd stage (300–499 °C), a drastic weight loss was found in PA with NS samples. It could be attributed due to the evolution of monomers and styrene present in PA aggregates. Similar results were also reported previously between 300 and 350 °C in plastic aggregates (Suzuki & Wilkie, 1995). Subsequently, control sample lost its maximum weight of 14.04% between 700 and 800 °C. This temperature is similar to clinker temperature, so de-carbonization might have happened leading to weight reduction. The overall weight loss of PA with NS sample and control samples are 86.30% and 23.42%, respectively. Figure 20 shows the thermos gravimetric performance.

5 Conclusions

According to the study, the partial substitution of PA in concrete alters the properties, such as fresh, density, stress–strain behavior, Poisson's ratio and modulus of elasticity of concrete; meanwhile, 5% inclusion of NS with PA exhibited a slight enhancement except fresh property. The thermal performance of control and maximum PA substituents with NS also examined. Based on this experimental study the following conclusions are made:

- The partial substitution of 20% PA in concrete enhances the slump value around 77%, which might be because of the spherical shape and non-absorbing water properties of PA.
- The dry density of 20% PA substation in concrete exhibits the maximum density reduction of 15.45% without NS. Meanwhile, the addition of NS with PA exhibits a slight enhancement in dry density, which was around 1.6% that could be due to the low density of PA and NS compared to conventional aggregate.
- Upon 20% of PA substitution, the maximum compressive strength reduction of 49.18% was observed. However, the inclusion of NS with PA showed an enhancement of strength development. On other hand, PA inclusion in concrete highly affected the split tensile strength which was around 65% at 20% replacement level.
- The stress–strain relationship of concrete with PA inclusion indicates greater ductility and strain failure compared to control concrete. Notably, PA substitution up to 10% in concrete results in higher strain values, but beyond this point, the strain values decrease. Similarly, the *E* value of the concrete decreases as the PA content increases. Specifically, samples with 20% PA and 5% NS exhibit the most significant reduction in *E* value among all PA-substituted samples.
- Visual inspection of PA reveals a spherical shape, while its morphology displays a highly porous structure. The crack widths observed in the control, 20% PA, and 20% PA with NS samples ranged from 1 to 5 µm, 5–13 µm, and 3–6 µm, respectively. This indicates that the inclusion of PA alone increases the crack width in concrete, which negatively impacts its strength and durability. However, addition of NS reduces the crack width.
- The thermal efficiency analysis (both indoor and outdoor performance) of concrete samples indicate that the inclusion of PA with NS reduces the thermal conductivity, which could lead to the enhanced the energy efficiency of the structures.

Abbreviations

ITZ	Interfacial Transition Zone
NA	Natural aggregates
PA	Plastic coarse aggregate
NS	Nano-silica
RPA	Recycled plastic aggregates
E-waste	Electronic waste
OPC	Ordinary Portland Cement
ASTM	American Society for Testing and Materials
TGA	Thermo-gravimetric analysis
SEM	Scanning Electron Microscopy
XRD	X-ray diffraction

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Author contributions
D. K: writing—review/editing, formal analysis, data collection, conceptualizations, formal analysis, investigation, design, experimentation, and writing original/final draft. A.G.A: conceptualizations, formal analysis, investigation, design, experimentation, writing original/final draft, writing—review/editing visualization, supervision and project administration. PAJ: writing—review/editing visualization supervision and project administration. RDK writing—review/editing visualization and data analysis. All authors read and approved the final manuscript.

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Data availability
All the data associated with this study are available from the corresponding author upon request.

Declarations

Ethics approval and consent to participate
All authors of the manuscript confirm the ethical approval and consent to participate following the Journal's policies.

Consent for publication
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