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Optimum Use of Recycled Waste Materials as Partial Replacement of Fine Aggregate in Portland Cement Concrete Mixes

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ABSTRACT

This study explored the independent utilization of five common waste materials - rubber, plastic, glass, slag, and sewage sludge ash (SSA) - as partial replacement of fine aggregate in Portland cement concrete (PCC) mixes. The main objective was to determine an optimum substitution range for each waste material that would offer well performing concrete in terms of workability, compressive strength, and durability. To this end, multiple concrete batches were prepared, incorporating each waste material at four different levels: 5%, 10%, 15%, and 20% by weight of fine aggregate. Then, concrete samples (100-mm diameter × 200-mm tall cylinders) were cast from each batch and were moisture-cured for 7, 14, and 28 days prior to testing. Also, the chemical composition of each waste material was identified using FTIR spectroscopy to understand its impact on the development of concrete strength. While most waste led to the diminished strength gains at all substitution rates, the addition of glass, slag, and SSA contributed positively to the strength development at specific replacement levels: 5% for glass, 10 - 15% for slag, and 5 – 15% for SSA. Furthermore, these additions of glass and slag exhibited comparable workability and durability although SSA did not exhibit comparable workability and durability. The findings of this study can hold significant implications for environmental sustainability and cost effectiveness in construction projects.

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Introduction

The proliferation of industrial and household waste has become a pressing global issue, leading to significant environmental challenges. In response, various waste management measures are being employed, both proactive and reactive, to minimize the amount of waste being sent to landfills. The use of secondary (recycled) waste materials instead of primary (virgin) materials helps reduce the landfill pressures and reducing demand of extraction [1]. However, the effectiveness of these measures varies depending on the type of waste, not necessarily the amount generated. Some waste materials are successfully managed through recycling, composting, or combustion, while others are handled in less favorable ways, ultimately ending up in landfills [2].

In the United States, paper and food waste were responsible for more than 50 percent of the total Municipal Solid Waste (MSW) generated in 2018. However, these waste categories achieved a notable recycling rate of 70 percent, equivalent to over 100 million tons. In fact, less than 5 percent of the collected paper and food waste were sent to landfills after being composted or combusted efficiently. Conversely, rubber, glass, and plastics generated in the same year were primarily destined for landfills. The recycling rates for these materials were quite low, ranging from 8.4 percent for plastics to 25 percent for glass. The option of combustion with energy recovery was rarely pursued due to the high associated costs and concerns about air pollution [3]. The significant disparity in recycling rates among waste can be partially attributed to the limited identification or development of uses for these seldom recycled waste materials. Therefore, it is crucial to emphasize extensive research focused on identifying non-hazardous and economically viable waste utilization methods.

Several methods of waste utilization have been developed and tested in the construction industry, particularly for roads and soil structures. While some waste is directly used as primary construction material most recycling techniques aim to enhance the performance of virgin material by capitalizing on the inherent properties, whether physical or chemical, of the recycled waste. Waste materials that are frequently used in this field include rubber, plastic, glass, slag, and SSA.

Scrap tires and leather, which are abundant sources of rubber, are shredded or ground into different sizes. Rubber chips or granules are then bonded together with adhesive to create surfaces for bicycle lanes, playgrounds, and pedestrian roads

[4-6]. Alternatively, crumb or powdered rubber can be combined with an unaged asphalt binder at high temperatures to produce a modified asphalt binder. This crumb rubber modified asphalt exhibits greater resilience under heavy traffic loading compared to traditional asphalt, reducing the likelihood of cracks in cold regions [7, 8].

Certain pilot tests have indicated that incorporating recycled plastic strips into soils can enhance the stabilization of embankments [9]. Polyethylene terephthalate (PET) products, such as bottles, cups, and bags, consist of polyethylene, polyvinyl chloride, polystyrene, and polypropylene. These components can serve as valuable additives in asphalt concrete mixes or modifiers for asphalt binders [10-13].

Glass particles can provide similar physical properties to sand, serving as a substitute for depleting natural sand in various construction applications [14]. Additionally, recycled glass is utilized to enhance the performance of asphalt pavements by minimizing cracks and permanent deformation. This improvement is due to the combined effect of silica, limestone, and soda ash present in the glass on the viscosity of asphalt binder, as well as formation of void structures in asphalt concrete mixtures [15].

Slag obtained from steel mills share similar chemical characteristics with scrap metals, containing significant amounts of chemical elements like Fe, Ca, Si, Mn, Al, and Mg [15]. Steel slag is classified into two types: basic black slag and basic white slag. The former has a lime content of less than 40% and results from the cold loading of scrap, while the latter has a lime content greater than 40% and is generated during fining, where additional lime is added to remove sulfur and phosphorus. Steel slag is commonly utilized in concrete as supplementary cementitious material, aiding in achieving desired levels of strength, durability, and functionality. A study demonstrated that up to 45% by weight of cement could be replaced with steel slags without compromising concrete strength [16].

Sewage sludge ash (SSA) is produced through the incineration of treated and dewatered sewage sludge, with global SSA generation exceeding 19 million tons annually [17]. SSA is characterized by low organic content, dryness, and non-plasticity. It is typically considered a silty material with some sand-sized particles, while also containing oxides like CaO, Al_2O_3, Fe_2O_3, MgO, and P_2O_5 [17-19]. SSA finds wide applications in land reclamation and is utilized in the production of cement, concrete, tiles, and bricks [20-23]. It is commonly used as aggregates in cement mortar, concrete, and asphalt concrete mixes or as soil stabilizers in combination with cement, nano-aluminum oxides, and fly ash [24-29].

Previous research has demonstrated the promising outcomes of utilizing waste in construction and building materials, which encompass performance, economic, and environmental benefits. However, there is still a lack of practical designs for those recycled materials. Addressing this gap, a laboratory study was conducted to investigate the individual utilization of five waste materials - rubber, plastic, glass, slag, and sewage sludge ash (SSA) - as partial replacements for sand in Portland cement concrete mixes. The primary objective of this study was to determine the optimal substitution rate for each waste material leading to the formulation of concrete mixes that result in good performance in terms of workability, compressive strength, and durability. To achieve this goal, multiple concrete batches were prepared, incorporating each waste material at four different levels: 5%, 10%, 15%, and 20% by weight of sand. Concrete samples in the form of cylinders with 100-mm (4-inch) diameter and 200-mm (8-inch) height were cast from each batch and cured for 7-, 14-, and 28-days prior testing. Additionally, the chemical characteristics of each waste material were analyzed using FTIR to support the understanding of strength development mechanisms and the evolution of microstructure in recycled concrete. The optimized utilization of these waste materials in concrete not only holds the potential to bolster effective waste management practices, also promises to reduce disposal costs, and mitigate reliance on raw materials for construction purposes [2]. Furthermore, it aligns with the current waste management goals as underscored by recent literature [30].

Materials and Experimental Program

Waste Materials

Five waste materials tested in this study were collected from multiple recycling facilities and one wastewater treatment plant across the state of Georgia.

Figure 1 shows the samples of rubber (Global Alliance, Atlanta), plastic (US Plastic Recovery, Lawrenceville), glass (Strategic Materials, College Park), slag (TMS International, Cartersville), and SSA (RL Sutton Wastewater Reclamation Facility, Smyrna).

Figure 1: Five Waste Material Samples-Physical Appearances

Figure 2 shows a gradation chart for developed for five waste materials along with sand (designated as #810 fine aggregate), extending up to No. 4 sieve-size (4.75-mm). Also, the fineness modulus (FM) was measured according to ASTM D2497. It is evident that the particle sizes of rubber, plastic, and glass were much coarser than SSA and slag. Visual inspection confirmed this observation, revealing gradation curves for these samples closely resemble a typical one-sized gradation. Slag and sand displayed comparable particle sizes and were characterized as well graded curves. SSA was the finest material among the samples with the FM of 1.22.

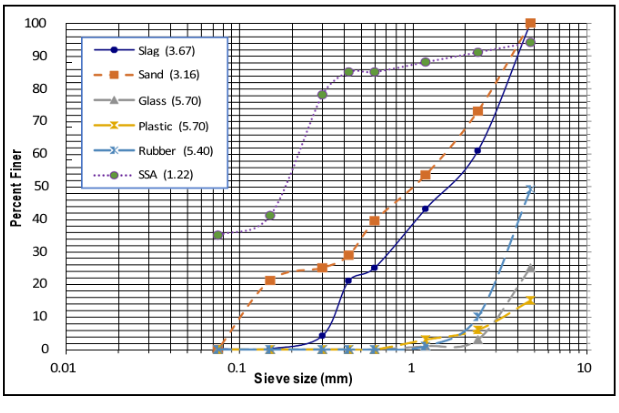

Figure 2: Particle Size Distribution of Waste Materials and Fine Aggregate and FM in Parenthesis

Concrete Batches and Samples

Table 1 presents key design parameters and their corresponding target values utilized for the control mix. Type I/II cement sourced from Leigh Hanson Company in Doraville, GA was batched with aggregate blends. Both stone (designated as #57 coarse aggregate) and #810 sand were obtained from a quarry in Augusta, GA. In the case of the recycled batches, most of the target values remained consistent with those of the control mix. However, a fraction of sand was replaced by waste materials at four different rates: 5%, 10%, 15%, and 20% by weight of sand. It should be noted there are no other cementitious materials than Portland cement in any of concrete batches to better evaluate the effects of waste utilization on strength gain. Further, no chemical admixture was added.

Table 1: Concrete Mixture Design for Control Batch

Ingredient	Target
Cement (type I/II)	448.52 kg/m^3 (28.0 lb/ft3)
Sand (#810)	744.86 kg/m^3 (46.5 lb/ft3)
Stone (#57)	983.54 kg/m^3 (61.4 lb/ft3)
Water	201.83 kg/m^3 (12.6 lb/ft3)
Strength (28-day)	20.68 MPa (3,000 psi)

After mixing, fresh concrete was sampled from each batch for the workability check and then cast into 100-mm (4-inch) diameter and 200-mm (8-inch) tall cylinders for moisture curing. The hardened concrete cylinders were tested for performance evaluations at 7, 14, and 28 days. For each waste material, nine cylinders were prepared at each waste content.

Experimental Program

Laboratory experiments consisted of chemical structure analyses on waste materials and performance evaluations of concrete. The Fourier transforms infrared spectrometer (FTIR) spectroscopy (PerkinElmer Spotlight 200i FTIR Microscope System) was used to identify the chemical structure in each waste material, while the performance of concrete was evaluated in terms of workability of fresh concrete and the durability and strength of hardened concrete.

The FTIR analyses were based on the peak numbers counted in six band ranges of spectrum that describes various states of chemical elements and their bonded forms, such as $Ca(OH)_2$ -OH, H-O-H, Si-O- Si, $CaCO_3$ [31, 32]. The detailed chemical composition analyses and microscopic visualizations of waste particles were not part of this experimental effort.

Following procedures specified in ASTM C143, the workability of fresh concrete was checked with slump measurements for both the control and recycled batches. With the slump values compared between the batches, one can understand how recycled waste should affect workability. Conventional slump controllers like water and admixtures were not part of the testing variables.

A surface resistivity technique (the Wenner probe) was employed to test concrete durability according to AASHTO TP9. A main hypothesis was that waste materials incorporated should change pore size distribution and the shape of the interconnections in the concrete's microstructure, and thus influence the service life of concrete under adverse environmental conditions. The evolution of resistivity was collected from the surface of concrete cylinders aged at 7, 14, and 28 days. All concrete samples tested for durability were crushed under uniaxial compressive loading for strength evaluation. Test setups and procedures described in ASTM C39 were followed and a servo hydraulic loading machine (Humboldt) was used to capture the peak load.

The collected data from all performance tests were processed to evaluate the impact on waste utilization on concrete. The findings, in part supported by the FTIR results, would result in the optimum range of recycling rates suitable for each waste material.

Results and Discussions

Chemical Structure of Waste Materials

The FTIR analysis of the waste materials is shown in Figure 3 and Table 2. Table 2 shows the FTIR peak numbers counted in six band areas for each waste material and total peak numbers ranging 2 to 8 [33].

Table 2: FTIR Peak Number of Waste Materials

Band Range (cm^{-1})	Indication	Peak number				
		Rubber	Plastic	Glass	Slag	SSA
4000 – 3500	Loss of $Ca(OH)_2$	0	0	1	1	1
3500 - 1600	Stretching (-OH), bending (H-O-H)	0	0	0	0	1
1600 - 1000	Gains Si-O-Si bands typical of quartz	0	1	3	2	1
1000 – 800	Loss of gel $CaCO_3$	1	2	2	1	3
800 - 500	Symmetric stretching of Si-O-Si and Al-O-Si	1	1	1	1	1
< 500	Bending vibrations of Si-O-Si and O-Si-O bonds	0	1	1	1	1
		2	5	8	6	8

Glass and SSA scored highest, followed by slag, plastic, and rubber. Nevertheless, glass, slag, and SSA have close band area numbers. The similarity of the band area 3500-1600 cm^{-1} indicates the (-OH) bond stretching and the (H-O-H) vibrations bending of bound water molecules, entrapped in polymeric framework cavities and absorbed on the surface; only SSA showed similarity in this band area. The similarity of the band area 1600-1000 cm^{-1} indicates the gains in the Si-O-Si bands typical of quartz and glass, and slag showed the highest similarity in this band. The similarity of the band area 800-500 cm^{-1} indicates the symmetric stretching of the Si-O-Si and Al-O-Si bonds, describing the formation of amorphous to semi-crystalline alumino-silicate materials. As seen in Figure 3 all the waste materials showed these similarities. The similarity of the band area below 500 cm^{-1} indicates the bending vibrations of the Si-O-Si and O-Si-O bonds. All materials except rubber showed this similarity.

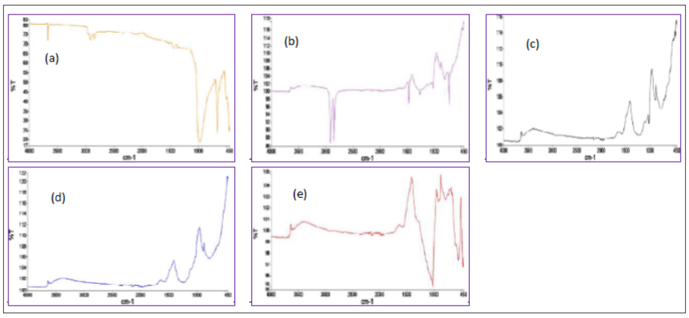

Figure 3: Standard FTIR Spectrum Chart: (a) rubber (b) plastic (c) glass (d) slag (e) SSA

Impact of Waste on Workability

Figure 4 summarizes the slump values (workability) measured from all fresh concrete samples. Overall, slump significantly increased from the control batch (0% waste content) as the waste content increased for rubber, glass, and plastic. This may indicate that these materials are less capable of absorbing and holding water in their surface voids than sand particles, releasing enough free moisture to increase the workability.

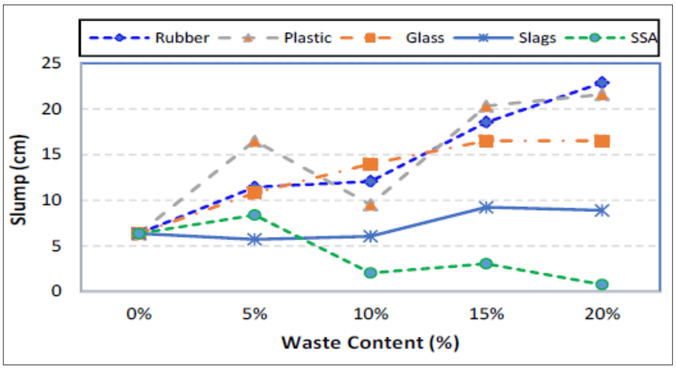

Figure 4: Workability of PCC mixed with waste materials

The impact of slag on slump was not as pronounced as other coarse waste materials (plastic, rubber and glass) at lower contents, but slump increased almost at the same rate as that of glass at higher rates (15 and 20 percent). However, SSA inclusion seems detrimental to the workability of concrete. As illustrated in gradation (Figure 2), a much higher surface area in SSA than sand particles may have caused a higher volume of surface voids that consume waste in concrete mixes.

Impact of Waste on Strength and Durability

Rubber

As seen in Figure 5, there was a noticeable decline in strength as the rubber content increased. This is likely attributable to the greater volume of entrapped voids resulting from the presence of coarse rubber particles. Further, FTIR analysis illustrated in Figure 3 reveals that hydrated concrete samples did not contain any reactive chemicals facilitating bonding and enhancing strength. Efforts were made to ascertain the optimum rubber content that would yield compressive strength at least equivalent to, if not exceeding, that of the control mix.

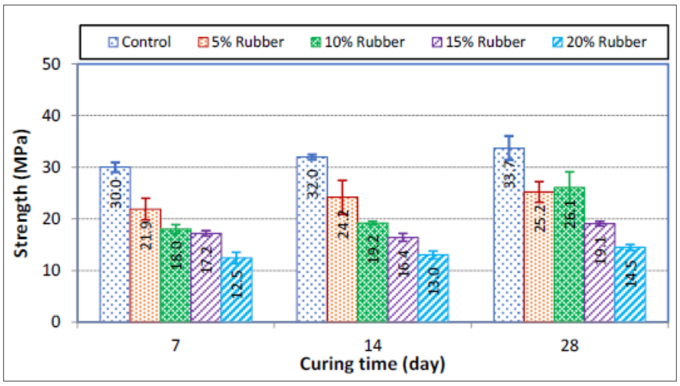

Figure 5: Compressive strength of PCC Mixed with Rubber

In Figure 6(a), the resistivity-an indicator of concrete durability-decreased as the rubber content increased at each age, except for the 14-day mark. Figure 6(b) exhibits some positive correlations between strength and resistivity at 7 and 28 days. Previous studies demonstrated that concrete strength should be directly linked to chloride permeability and chloride diffusion coefficient, irrespective of the mix design parameters [34]. Furthermore, some research has suggested connections between strength and rheological properties, such as yield stress and plastic viscosity [35]. Although rubber can improve workability, it consistently compromised the early strength gains. Consequently, rubber may not be a viable option as a fine aggregate replacement in PCC mixes.

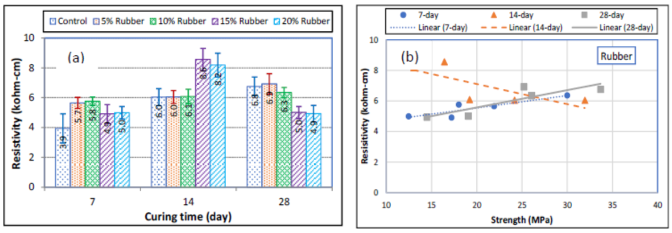

Figure 6: Durability of PCC Mixed with Rubber

Plastic

As Figure 7 depicts, strength decreased with the increased plastic contents in part because of coarser plastic particles than sand. Also, FTIR data on plastic samples (as illustrated in Figure 3b) revealed that there were no significant reactive chemicals that could contribute to enhanced bonding and increased strength. Interestingly, plastic mixes resulted in higher strengths compared to rubber mixes with equivalent waste contents. This could be due to differences between the peak intensities (rubber = 2, plastic = 5) as presented in Table 2.

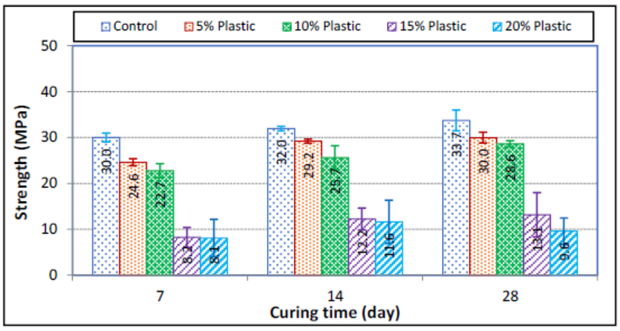

Figure 7: Compressive Strength of PCC Mixed with Plastic

Durability appeared to improve with plastic content compared to the control, particularly evident during 7-day and 28-day curing periods (Figure 8a). However, this trend was not consistent across all curing periods. Mostly zero to negative correlations between durability and strength were observed for plastic for all the curing periods (Figure 8b). Although higher workability can be achieved using plastic as a replacement for fine aggregate, the strength requirements cannot be met compared to the control. As a result, plastic might not be a viable fine aggregate replacement option in PCC mixes.

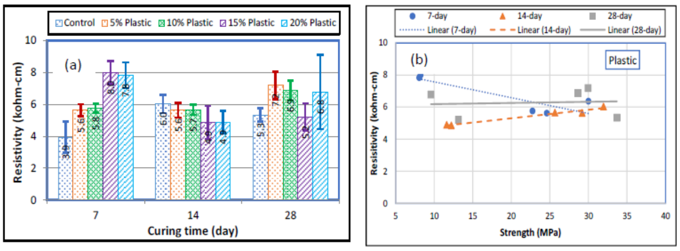

Figure 8: Durability of PCC Mixed with Plastic

Glass

Figure 9 shows that the strength increased with the increased plastic contents, at least for 5% glass content, for all curing periods. This could be due to the angularity features and the coarse nature of glass compared to sand contributing to the strength. The other reason could be that glass is composed of silica or sand and contains some amounts of limestone and soda ash that may contribute to the cementing capacity of the PCC mix [9]. FTIR analysis did show reactive chemicals such as Si-O-Si bands typical quartz and loss of gel $CaCO_3$ (Figure 3c) that can create bonding and help increase the strength.

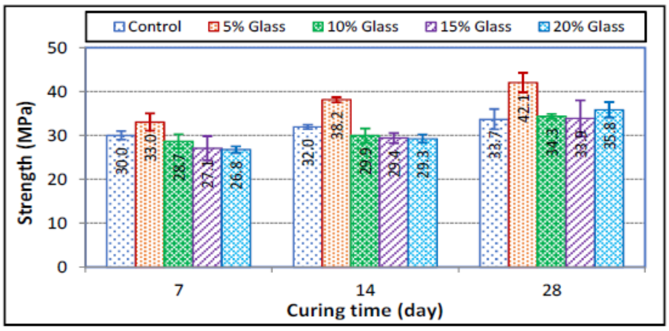

Figure 9: Compressive Strength of PCC Mixed with Glass

The durability increased with increased glass content compared to the control at least for 14-day and 28-day curing periods (Figure 10a), although the 7-day curing period did not follow the same trends. Some positive correlations between durability and strength were observed for 7- and 14-day curing periods and a slight negative correlation for the 28-day curing period (Figure 10b). Both workability and strength can be achieved using glass as a replacement for fine aggregate. Since the glass is easily available and cheaper, glass might be a viable fine aggregate replacement option in PCC mixes.

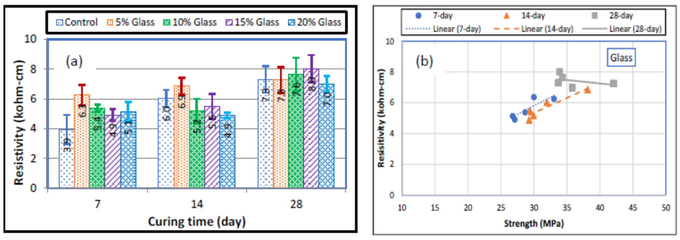

Figure 10: Durability of PCC Mixed with Glass

Slag

Strength increased with the increased slag contents dominantly for 10% and 15% slag contents for the 14- and 28-day curing periods (Figure 11). Since the gradation of slag is similar to that of sand, the replacement would not contribute to the strength gains by the increased interlocking motion among the particles. FTIR analysis supported and showed reactive chemicals such as Si-O-Si bands typical quartz and loss of gel $CaCO_3$ (Table 2) that can create bonding and help increase the strength.

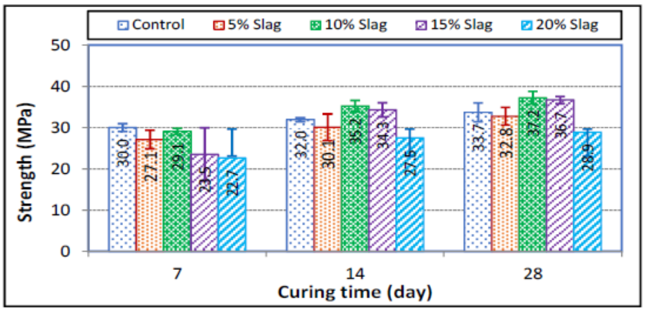

Figure 11: Compressive strength of PCC Mixed with Slag

The durability decreased in all cases except for 5% slag content for a 14-day curing period (Figure12a). Some positive correlations between durability and strength were observed at least for 7-day curing periods and slightly negative or zero correlations were observed for the other two curing periods (Figure12b). Although workability is not favorable, based on the strength consideration, slag could be a viable fine aggregate replacement option in PCC mixes.

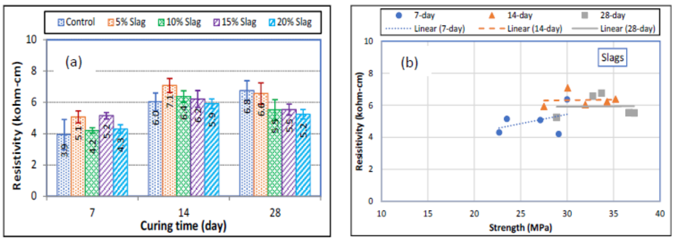

Figure 12: Durability of PCC Mixed with Slag

SSA

Strength increased with the increased SSA contents dominantly for 5% and 10% SSA contents for all the curing periods (Figure 13). Strength also increased with increased SSA contents for 15% for the 7-day and 14-day curing periods and remained close to control for 20% SSA content (Figure 13). FTIR analysis indicated the presence of multiple reactive chemicals (Figure 3e) that can increase the internal bonding to increase the strength. This could be an obvious finding as the results (Figure 13) for all curing periods that showed an SSA content of 5% to 15% could be optimum. The increase of compressive strengths with the increase of SSA contents could be due to the chemical reaction of the SSA with the soil represented by the deposition of some mineral such as Calcium Carbonate inside the pores of sand-SSA matrix that resulted in plugging the pores in the mixture resulting in reducing the sand-SSA mix permeability and increasing its strength. Another potential reason could be the contribution of the angular glassy spheres of SSA grains which increased the bonds among sand particles [36]. This study also supports a study [22] that found SSA inclusion in the PCC improved strength parameters and frost resistance as well as satisfied the environmental requirements imposed on leaching of heavy metals.

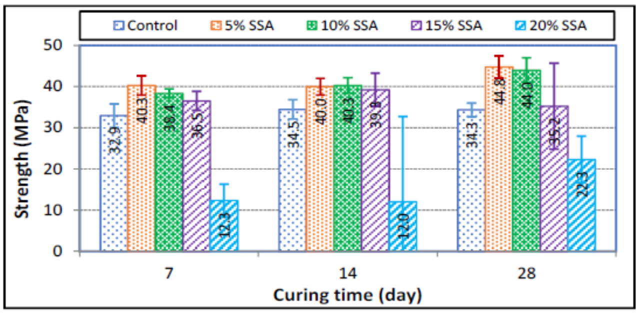

Figure 13: Compressive Strength of PCC Mixed with SSA

The durability seemed to increase randomly for several SSA contents for all three curing periods (Figure 14a). No positive correlations between durability and strength were observed for any of the curing periods (Figure 14b). Although strength is favorable for 5 – 15% SSA content. the workability is not favorable beyond 5% SSA content (Figure 4). Therefore, SSA may not be considered a viable fine aggregate replacement option in PCC mixes in terms of workability.

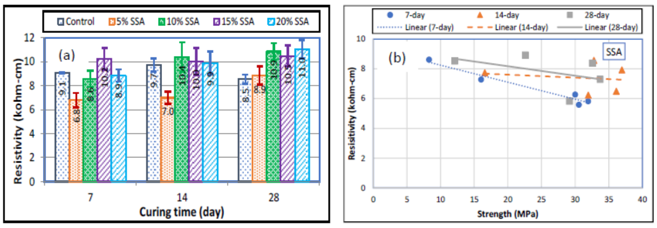

Figure 14: Durability of PCC mixed with SSA

Conclusions, Recommendations, and Future Research

From this study, the potential benefits of replacing the fine aggregate with recycled waste materials within concrete mixes include the reduction of waste materials destined for landfills and the cost savings for fresh raw materials. With regards to the specific rubber, plastic, glass, slag, and SSA produced in the USA and used in this study, several conclusions and recommendations can be made. However, there are few questions such as what happens if several of the waste mixed together and used to replace fine aggregate. To answer this question, we may need to study further by the combinations of waste materials to replace fine aggregate in the same mix.

Conclusions

Although high workability and moderate durability were obvious for several percentages of rubber and plastic contents in concrete, no rubber and plastic contents provided a meaningful strength gain that were at least equal to or greater than that of the control. As a result, this study does not recommend including rubber and plastic in concrete mixes as fine aggregate replacements. The optimum glass content appeared to be 5%. Five percent glass content provided reasonable workability and durability compared to the control. An optimum slag content appeared to be between 10% and 15% for providing strengths greater than or equal to the control as well as reasonable workability and durability. An optimum SSA content appeared to be between 5% and 15% for providing strengths greater than or equal to the control although SSA does not show reasonable workability and durability compared to the control. A further study of SSA is necessary to ascertain the reasonable and favorable workability and durability before recommending SSA. Based on the study, no empirical correlation between surface resistivity (durability) and strength can be established.

Recommendations and Future Research

Due to the varying chemical compositions of the waste materials generated in different areas, these study results may not be used blindly, and more rigorous and comprehensive investigations on the performance of these materials as well as the combinations of waste materials to replace fine aggregate in the same mix are needed in future research.

Author Contributions

Conceptualization, M.A.K. and Y.S.; methodology, M.A.K. and Y.S.; formal analysis, M.A.K. and Y.S.; investigation, M.A.K., Y.S., B.V., K.R., C.P., M.H. and A.Y; resources, M.A.K. and Y.S; data curation, B.V., K.R., C.P., M.H. and A.Y.; writing original draft preparation, M.A.K.; writing—review and editing, M.A.K. and Y.S.; visualization, M.A.K., B.V., K.R., C.P., M.H. and A.Y.; supervision, M.A.K. and Y.S.; project administration, M.A.K. and Y.S.; funding acquisition, M.A.K. and Y.S. All faculty authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

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Informed Consent Statement

Not applicable.

Data Availability Statement

The data presented in this study are available upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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