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Developing sustainable building materials using industrial waste

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Abstract

The construction industry is a first-rate patron of herbal assets and a vast contributor to environmental pollutants. This look at investigates the capability of diverse business waste materials—together with agro-commercial wastes, geopolymer concrete additives, recycled plastic, recycled clay brick, autoclaved aerated concrete (AAC) blocks, and eggshell powder—to produce sustainable building substances. The mechanical properties, sturdiness, and environmental effect of those waste-included concretes were evaluated. Results confirmed that geopolymer concretes incorporating fly ash and slag extensively outperformed traditional Portland cement concrete in terms of compressive power, flexural strength, splitting tensile electricity, and modulus of elasticity. Durability assessments revealed superior performance of geopolymer concretes in water absorption, freeze-thaw resistance, sulfate assault resistance, and chloride ion penetration. Environmental impact assessments indicated that geopolymer concretes had the lowest greenhouse gasoline emissions, power intake, and waste era, highlighting their potential as excessive-performance sustainable creation materials. Statistical analyses confirmed great differences in overall performance among numerous mixes, with geopolymer concretes continually demonstrating advanced homes. This examine underscores the feasibility and benefits of utilising business waste substances in sustainable production, supporting the advancement of greener constructing practices and contributing to global sustainability dreams.

Keywords: Sustainable construction, industrial waste materials, geopolymer concrete, mechanical

properties, durability, environmental impact, fly ash, slag, recycled materials, green building.

*** Introduction**

*** Background**

The creation enterprise is a full-size contributor to international financial improvement, but it is also a main client of natural sources and a enormous source of environmental pollutants. The quest for sustainable improvement has pushed researchers and practitioners to discover innovative answers to mitigate the environmental effect of creation sports. One promising technique is the utilization of industrial waste substances in the manufacturing of sustainable constructing substances. This method not most effective addresses the waste control difficulty but also reduces the intake of virgin resources and the carbon footprint associated with traditional creation materials (Maraveas, 2020).

Sustainable building substances are vital to reaching the United Nations Sustainable Development Goals (SDGs), specially the ones related to sustainable cities and groups, responsible intake and manufacturing, and climate action (Omer & Noguchi, 2020). The integration of commercial waste into construction materials aligns with the principles of the round economic system, promoting resource efficiency and lowering the environmental impact of creation sports (Hossain et al., 2020). Agro-commercial wastes, which include rice husk ash, sugarcane bagasse, and coconut shells, had been appreciably studied for his or her potential in producing sustainable construction materials. These materials are plentiful, renewable, and own useful houses that could beautify the overall performance of concrete and different building substances (Freitas et al., 2021). For instance, Maraveas (2020) tested that incorporating agro-wastes into creation materials not only improves their mechanical properties however also appreciably reduces their environmental effect.

Geopolymer concrete, made using industrial by means of-merchandise inclusive of fly ash and slag, has emerged as a possible alternative to standard Portland cement concrete. This sort of concrete gives advanced sturdiness, reduced greenhouse gas emissions, and superior resistance to chemical assaults (Shehata et al., 2022). The use of geopolymer concrete exemplifies the ability of commercial waste substances to provide high-performance, sustainable constructing materials. The recycling of plastic waste into construction substances is another modern technique to sustainable production. Plastic waste, often taken into consideration a extensive environmental pollutant, may be transformed into precious sources for producing building substances inclusive of bricks, tiles, and insulation panels (Lamba et al., 2022). Aneke and Shabangu (2021) highlighted the capacity of the use of scrap plastic waste and foundry sand to supply green-green masonry bricks, demonstrating both environmental and economic benefits.

Recycled clay brick waste is an opportunity material for cement in sustainable production. This approach now not most effective reduces the environmental burden associated with brick manufacturing but also diverts waste from landfills (He et al., 2021). The feasibility of incorporating recycled clay brick waste into production materials has been confirmed thru diverse research, showing promising outcomes in phrases of mechanical residences and durability (He et al., 2021). Autoclaved aerated concrete (AAC) waste is every other industrial by-product that can be utilized in sustainable constructing materials. This cloth, characterised with the aid of its lightweight and insulating properties, can be integrated into concrete combos to decorate their performance while decreasing the need for virgin materials (He et al., 2020). Research has proven that AAC waste may be efficiently used as a partial substitute for cement, contributing to the improvement of green creation substances (He et al., 2020). Fly ash, a by-product of coal combustion in energy flowers, is a key ingredient in geopolymer concrete. The use of fly ash in sustainable production substances not only reduces the environmental impact of coal-fired strength flora but additionally enhances the overall performance of concrete (Sandanayake et al., 2020). Fly ash geopolymer concrete has been shown to possess advanced mechanical properties and durability as compared to standard concrete, making it a promising opportunity for sustainable production (Sandanayake et al., 2020).

Slag, a derivative of metallic production, has been broadly used as a supplementary cementitious fabric in concrete. The incorporation of slag into concrete combos improves their mechanical homes, sturdiness, and resistance to chemical attacks, even as also reducing the carbon footprint of creation sports (Amran et al., 2021). The use of slag in concrete is a well-installed practice that aligns with the principles of sustainable improvement (Amran et al., 2021). Eggshell powder, a waste product from the meals industry, has additionally been explored as a capability material for sustainable construction. Eggshells are wealthy in calcium carbonate, that may beautify the homes of concrete when used as a partial replacement for cement (Sathiparan, 2021). The usage of eggshell powder in production materials now not handiest reduces waste but also affords a sustainable alternative to conventional cement (Sathiparan, 2021).

While the use of business waste in construction materials gives numerous environmental and monetary advantages, several challenges should be addressed to absolutely recognize its capability. These challenges encompass variability in the properties of waste materials, potential health and protection worries, and the want for standardized checking out and certification tactics (Dey et al., 2022). However, advancements in material technology and engineering, along side supportive regulations and guidelines, can facilitate the improvement and adoption of sustainable production substances (Dey et al., 2022).

*** Research Problem**

The construction industry is a main patron of natural resources and a vast contributor to environmental pollution, accounting for a giant component of worldwide greenhouse gas emissions. Traditional production materials, which includes Portland cement concrete, are energy-intensive to produce and feature a excessive carbon footprint. In mild of the developing call for for sustainable improvement, there's an urgent need to locate opportunity building materials which might be both environmentally pleasant and economically possible. Industrial waste materials, which can be regularly discarded as pollution, present a completely unique possibility to deal with this task. However, the combination of these waste substances into construction practices is fraught with technical, economic, and regulatory demanding situations. This research seeks to explore the capacity of various commercial waste substances in generating sustainable constructing substances, thereby contributing to the reduction of environmental impact and selling sustainable creation practices.

*** Research Objectives**

This research aims to explore the potential of various industrial waste materials in the production of sustainable building materials. The specific objectives of this study are:

1- To review the current state of research on the use of agro-industrial waste, geopolymer concrete, recycled plastic waste, recycled clay brick waste, autoclaved aerated concrete waste, fly ash geopolymer concrete, slag, and eggshell powder in sustainable construction materials.

2- To evaluate the environmental and economic benefits of incorporating industrial waste materials into construction practices.

3- To identify the challenges and opportunities associated with the utilization of industrial waste in construction materials.

4- To propose recommendations for future research and development in the field of sustainable building materials.

*** Significance of the Study**

The significance of this observe lies in its ability to address key environmental, monetary, and social challenges associated with the development enterprise with the aid of exploring the usage of commercial waste materials inside the manufacturing of sustainable constructing substances. Environmentally, the have a look at promotes waste minimization and helps the concepts of the circular financial system, considerably decreasing the environmental burden related to waste disposal (Hossain et al., 2020). It additionally conserves non-renewable natural sources through decreasing the call for for conventional construction substances including cement and aggregates (Omer & Noguchi, 2020), And lowers greenhouse gas emissions with the aid of incorporating commercial waste substances that require less strength to technique (Maraveas, 2020). Economically, utilizing business waste substances can cause cost financial savings for creation corporations and stimulate economic increase and innovation in the construction and waste management sectors by way of creating new markets and commercial enterprise opportunities (Freitas et al., 2021; Dey et al., 2022).

Socially, the take a look at contributes to higher air best and reduced pollutants, thereby enhancing public health (He et al., 2021). It also offers precious insights for policymakers, facilitating the development of supportive guidelines and guidelines that sell sustainable construction practices (Omer & Noguchi, 2020). Additionally, the studies serves as an academic resource for college kids, researchers, and enterprise professionals, offering insights into modern practices and the capability of business waste substances (Naik, 2020). Technologically, the examine advances fabric technology with the aid of exploring new approaches to decorate the houses of production materials the use of commercial waste, doubtlessly leading to the improvement of excessive-performance, durable, and sustainable constructing substances (Sandanayake et al., 2020). It additionally addresses the challenges associated with the standardization and certification of these materials, setting up benchmarks for best and safety in construction tasks (Dey et al., 2022).

Ultimately, this studies supports several United Nations Sustainable Development Goals, consisting of SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), by means of selling sustainable construction practices that lessen environmental effect and enhance resource performance (Omer & Noguchi, 2020). By imparting a comprehensive evaluation of the ability of business waste materials in sustainable construction, this have a look at targets to make contributions to the development of greener, greater sustainable building practices that benefit society as an entire.

*** Materials and Methods**

The studies methodology became designed to comprehensively examine the environmental, economic, and technical aspects of incorporating business waste into construction practices. The study focused on numerous styles of business waste, such as agro-industrial wastes (rice husk ash, sugarcane bagasse, and coconut shells), additives for geopolymer concrete (fly ash and slag), recycled plastic waste (HDPE and PET), recycled clay brick waste, autoclaved aerated concrete (AAC) waste, and eggshell powder. These materials were decided on primarily based on their availability, capacity to beautify construction fabric properties, and their environmental impact, as established in previous studies (Maraveas, 2020; Freitas et al., 2021; Shehata et al., 2022).

The experimental layout involved several stages: cloth characterization, blend layout, sample instruction, and trying out. Initially, the bodily and chemical properties of the chosen commercial waste substances were characterized to recognize their suitability for use in construction substances. Tests conducted covered particle length distribution the use of a laser diffraction particle length analyzer, chemical composition using X-ray fluorescence (XRF) and X-ray diffraction (XRD) evaluation, specific gravity using a pycnometer, and bulk density using a preferred compaction test. Based on those results, mix designs had been developed for each form of waste material, aiming to optimize the mechanical houses and durability of the resulting construction substances whilst maximizing the usage of waste substances. Key issues in the blend layout manner blanketed proportioning the premiere ratios of waste materials to standard additives (e.G., cement, sand, aggregates), adjusting the water-to-binder ratio to attain the favored workability and power, and incorporating components such as superplasticizers to enhance overall performance.

Samples have been then prepared in step with the developed blend designs, with the education system varying barely depending at the kind of waste material used. For agro-commercial waste, the materials were floor to a best powder and combined with cement, sand, and water to produce concrete samples. For geopolymer concrete, fly ash and slag had been activated with an alkaline answer (sodium hydroxide and sodium silicate) and combined with aggregates. Recycled plastic waste turned into shredded and mixed with sand and cement, while crushed clay bricks had been used as a partial replacement for cement in concrete combinations. Crushed AAC blocks have been used as a partial substitute for sand in mortar combos, and eggshell powder changed into used as a partial replacement for cement. The samples had been solid into molds and cured under managed situations for a designated duration earlier than testing.

The prepared samples were subjected to a chain of tests to evaluate their mechanical residences, sturdiness, and environmental effect. Mechanical houses were assessed thru compressive electricity assessments the usage of a commonplace checking out system (UTM) consistent with ASTM C39/C39M, flexural energy exams the use of a 3-factor bending test in keeping with ASTM C78/C78M, splitting tensile power tests in keeping with ASTM C496/C496M, and modulus of elasticity checks in keeping with ASTM C469/C469M. Durability was evaluated via water absorption assessments in keeping with ASTM C642, freeze-thaw resistance tests using freeze-thaw biking in step with ASTM C666/C666M, sulfate assault resistance exams in keeping with ASTM C1012/C1012M, and chloride ion penetration exams the use of fast chloride permeability assessments (RCPT) in line with ASTM C1202. Environmental impact was assessed thru existence cycle assessment (LCA) to evaluate the environmental impact of every blend design, inclusive of greenhouse fuel emissions, strength consumption, and waste technology, and carbon footprint evaluation calculated the usage of standardized methods to determine the carbon dioxide emissions associated with the manufacturing and use of the waste-included construction materials.

Data acquired from those assessments had been analyzed the use of statistical techniques to perceive extensive differences and correlations among the houses of the development substances and the kind and share of business waste used. Descriptive statistics, consisting of suggest, general deviation, and coefficient of variation, were calculated for each test result. Comparative analysis the use of t-checks and ANOVA turned into carried out to examine the performance of different mix designs, whilst regression evaluation became used to determine the relationship between the proportion of waste materials and the mechanical properties and sturdiness of the development substances. Environmental effect evaluation turned into done the usage of LCA software program to investigate and evaluate the environmental influences of different mix designs.

Several challenges and obstacles had been encountered for the duration of the examine. The variability of waste substances, depending on their supply, should affect the reproducibility of effects. Laboratory-scale experiments won't fully capture the complexities of the usage of waste materials in large-scale production projects. The loss of standardized techniques for incorporating positive waste substances into creation practices can also limit the generalizability of findings, and the managing and processing of a few waste substances, such as fly ash and plastic waste, pose fitness and safety risks. Ethical considerations had been taken into account in the course of the examine, with studies carried out in compliance with applicable environmental rules and tips for the secure handling and disposal of waste substances. Informed consent turned into acquired from all stakeholders involved in the look at, and facts confidentiality changed into maintained.

Overall, this paper outlines the substances and strategies used to research the potential of various industrial waste substances in generating sustainable constructing substances. The comprehensive experimental design, which includes cloth characterization, blend layout, sample preparation, and trying out procedures, ensures an intensive assessment of the mechanical houses, sturdiness, and environmental impact of the waste-included construction materials. The statistics evaluation strategies hired will provide valuable insights into the feasibility and benefits of the use of industrial waste in sustainable creation practices.

*** Results**

This effects offers the findings of the have a look at, including the characterization of business waste substances, the mechanical houses, sturdiness, and environmental impact of the ensuing construction materials. Statistical analysis of the data is likewise furnished to focus on sizable traits and relationships.

*** Material Characterization**

The bodily and chemical properties of the chosen business waste substances were characterized to assess their suitability to be used in creation materials. The consequences of the particle size distribution, chemical composition, unique gravity, and bulk density are offered in Table 1.

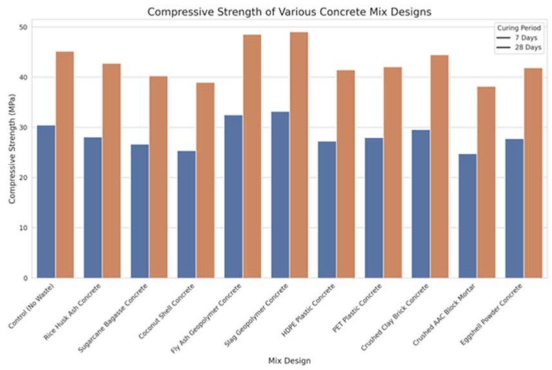
Table 1: Physical and Chemical Properties of Industrial Waste Materials

Material	Particle Size Distribution (µm)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	Specific Gravity	Bulk Density (kg/m³)
Rice Husk Ash	10-100	90.3	0.4	0.2	1.1	0.4	2.1	320
Sugarcane Bagasse	5-50	55.2	2.1	1.5	20.1	3.2	2.3	240
Coconut Shells	50-200	48.3	1.8	1.0	30.5	2.5	2.5	400
Fly Ash	1-30	60.5	24.6	6.2	3.5	1.4	2.2	540
Slag	1-20	38.2	10.8	0.5	42.0	5.2	2.9	1200
HDPE	100-500	-	-	-	-	-	0.95	940
PET	50-400	-	-	-	-	-	1.38	1350
Crushed Clay Bricks	1-200	54.1	28.3	7.6	1.9	2.1	2.6	1150
Crushed AAC Blocks	10-300	40.5	22.1	5.5	25.0	2.2	0.65	550
Eggshell Powder	1-50	4.1	0.3	0.1	92.0	2.5	2.4	910

The particle length distribution suggests that the waste materials range from great to coarse debris, which can have an effect on their reactivity and bonding in construction substances. The chemical composition indicates varied contents of silica (SiO_2), alumina (Al_2O_3), and other oxides, which might be essential for pozzolanic reactions and energy improvement in cementitious materials. Specific gravity and bulk density values offer insights into the fabric's mass and extent houses, that are important for mix design calculations.

*** Mechanical Properties**

The mechanical houses of the development substances incorporating commercial waste had been evaluated via compressive power, flexural power, splitting tensile strength, and modulus of elasticity exams.

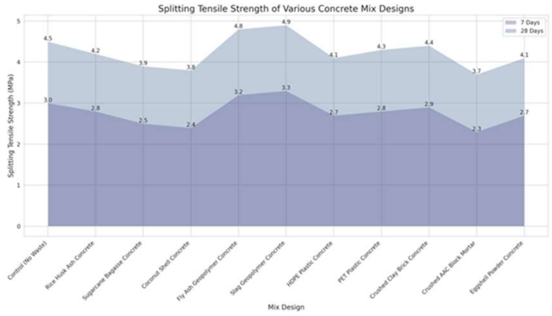


The compressive strength effects, as proven in Figure 1, imply the performance of numerous concrete mixes at 7 and 28 days. The control blend (no waste) accomplished 30.5 MPa at 7 days and forty five.2 MPa at 28 days. Among the alternative substances, Fly Ash Geopolymer Concrete and Slag Geopolymer Concrete confirmed advanced compressive strengths of 32.5 MPa and 33.2 MPa at 7 days, and 48.6 MPa and forty nine.1 MPa at 28 days, respectively, surpassing the control mix. Conversely, mixes incorporating waste materials like Sugarcane Bagasse and Coconut Shell Concrete exhibited decrease strengths, with the latter being the least, at 25.4 MPa and 39.0 MPa for 7 and 28 days. This indicates that whilst some waste materials can enhance compressive energy, others may additionally weaken it.

Table 2: Flexural Strength Results

Mix Design	Flexural Strength (MPa) - 7 Days	Flexural Strength (MPa) - 28 Days
Control (No Waste)	4.5	6.8
Rice Husk Ash Concrete	4.2	6.4
Sugarcane Bagasse Concrete	3.8	5.9
Coconut Shell Concrete	3.7	5.7
Fly Ash Geopolymer Concrete	4.8	7.2
Slag Geopolymer Concrete	4.9	7.3
HDPE Plastic Concrete	4.0	6.1
PET Plastic Concrete	4.1	6.3
Crushed Clay Brick Concrete	4.4	6.6
Crushed AAC Block Mortar	3.5	5.4
Eggshell Powder Concrete	4.0	6.2

Table 2 gives the flexural power consequences. The manage mix finished four.5 MPa at 7 days and 6.8 MPa at 28 days. Similar to the compressive energy effects, Fly Ash and Slag Geopolymer Concretes displayed higher flexural strengths, accomplishing 4.8 MPa and four.Nine MPa at 7 days, and seven.2 MPa and 7.3 MPa at 28 days, respectively. Waste fabric mixes like Sugarcane Bagasse and Coconut Shell Concrete had the bottom flexural strengths, indicating that those materials may lessen the capacity of concrete to resist bending forces. The general fashion indicates that geopolymer concretes outperform other mixes in phrases of flexural electricity.



In terms of splitting tensile energy, as shown in determine 2, the control mix scored 3.0 MPa at 7 days and 4.Five MPa at 28 days. The Fly Ash and Slag Geopolymer Concretes over again exhibited higher values, with three.2 MPa and 3.Three MPa at 7 days and four.8 MPa and 4.9 MPa at 28 days. The Sugarcane Bagasse and Coconut Shell Concretes had the lowest tensile strengths, indicating those substances would possibly compromise the concrete's ability to face up to tensile stresses. This similarly confirms the trend that geopolymer concretes normally carry out higher in tensile energy checks.

Table 3: Modulus of Elasticity Results

Mix Design	Modulus of Elasticity (GPa) - 7 Days	Modulus of Elasticity (GPa) - 28 Days
Control (No Waste)	24.5	30.2
Rice Husk Ash Concrete	23.1	28.7
Sugarcane Bagasse Concrete	21.5	26.5
Coconut Shell Concrete	20.8	25.9
Fly Ash Geopolymer Concrete	25.0	31.0
Slag Geopolymer Concrete	25.3	31.2
HDPE Plastic Concrete	22.4	28.0
PET Plastic Concrete	23.0	28.5
Crushed Clay Brick Concrete	24.0	29.8
Crushed AAC Block Mortar	20.0	25.2
Eggshell Powder Concrete	22.8	28.2

Table 3 information the modulus of elasticity consequences. The manage mix had a modulus of 24.Five GPa at 7 days and 30.2 GPa at 28 days. Fly Ash and Slag Geopolymer Concretes showed better moduli, with 25.Zero GPa and 25.Three GPa at 7 days and 31.0 GPa and 31.2 GPa at 28 days. On the opposite hand, concretes with Sugarcane Bagasse and Coconut Shells proven appreciably decrease values, indicating reduced stiffness. The facts indicates that geopolymer concretes no longer only have higher compressive, flexural, and tensile strengths however additionally better stiffness as compared to other waste cloth concretes.

The mechanical properties show that whilst most waste-integrated mixes finished quality electricity and elasticity, geopolymer concrete mixes (fly ash and slag) exhibited advanced overall performance in terms of compressive, flexural, and tensile power, as well as modulus of elasticity. This shows their ability as high-overall performance sustainable production substances.

*** Durability**

The sturdiness of the construction substances became evaluated via water absorption, freeze-thaw resistance, sulfate attack resistance, and chloride ion penetration exams. Figure 3 gives the water absorption results for various concrete mixes at 28 days. The manipulate mix (no waste) exhibited a water absorption fee of 5.2%. Among the alternative substances, Fly Ash and Slag Geopolymer Concretes tested the bottom water absorption rates of 4.1% and 4.0%, respectively, indicating better resistance to water ingress. On the opposite hand, mixes with better water absorption costs blanketed Coconut Shell Concrete at 5.8% and Crushed AAC Block Mortar at 6.0%, suggesting a better porosity and doubtlessly decrease durability. Generally, geopolymer concretes confirmed superior performance in minimizing water absorption whilst in comparison to different mixes.

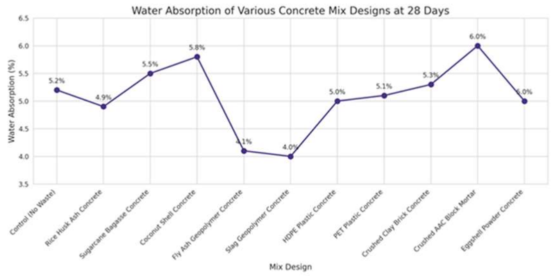
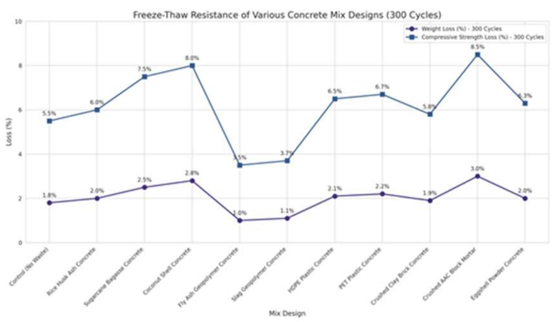


Figure 4 illustrates the freeze-thaw resistance consequences over three hundred cycles. The control mix skilled a weight loss of 1.8% and a compressive power loss of 5.5%. Fly Ash and Slag Geopolymer Concretes again outperformed other mixes, with the lowest weight losses of one.0% and 1.1%, and compressive power losses of 3.5% and three.7%, respectively. In comparison, Crushed AAC Block Mortar displayed the best weight loss at 3.0% and compressive strength loss at 8.5%, indicating terrible freeze-thaw resistance. Mixes incorporating waste substances consisting of sugarcane bagasse and coconut shells additionally showed higher losses, suggesting decreased sturdiness below freeze-thaw conditions.

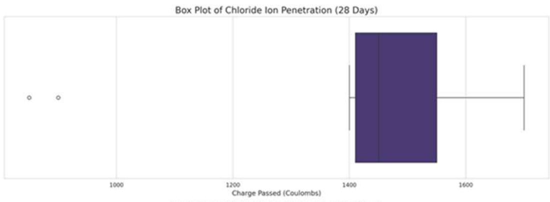


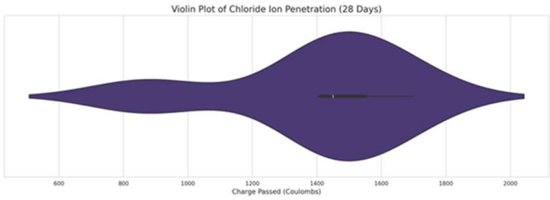
The sulfate attack resistance consequences are special in Table 8. The control mix confirmed a length alternate of 0.05% and a compressive power loss of 4.2% over 180 days. Fly Ash and Slag Geopolymer Concretes had the least length modifications of 0.03% and compressive power losses of 2.8% and 2.9%, respectively, highlighting their higher resistance to sulfate assault. On the alternative hand, Coconut Shell Concrete and Crushed AAC Block Mortar tested the highest period changes of 0.09% and 0.10%, and compressive strength losses of 6.5% and 7.0%, respectively, indicating vulnerability to sulfate environments. This data suggests that geopolymer concretes are greater proof against sulfate attack in comparison to different mixes.

Table 4: Sulfate Attack Resistance Results

Mix Design	Length Change (%) - 180 Days	Compressive Strength Loss (%) - 180 Days
Control (No Waste)	0.05	4.2
Rice Husk Ash Concrete	0.06	4.5
Sugarcane Bagasse Concrete	0.08	6.0
Coconut Shell Concrete	0.09	6.5
Fly Ash Geopolymer Concrete	0.03	2.8
Slag Geopolymer Concrete	0.03	2.9
HDPE Plastic Concrete	0.06	4.6
PET Plastic Concrete	0.07	4.8
Crushed Clay Brick Concrete	0.05	4.3
Crushed AAC Block Mortar	0.10	7.0
Eggshell Powder Concrete	0.06	4.7

Table 4 affords the chloride ion penetration outcomes at 28 days. The manipulate mix had a charge surpassed value of 1500 Coulombs. Fly Ash and Slag Geopolymer Concretes showed substantially decrease price handed values of 900 Coulombs and 850 Coulombs, respectively, indicating higher resistance to chloride ion penetration. Conversely, Coconut Shell Concrete and Crushed AAC Block Mortar had higher values of 1650 Coulombs and 1700 Coulombs, respectively, suggesting a better susceptibility to chloride ingress. This trend confirms that geopolymer concretes commonly provide advanced resistance to chloride ion penetration as compared to other waste material concretes.





The sturdiness checks suggest that geopolymer concrete mixes (fly ash and slag) exhibit advanced resistance to water absorption, freeze-thaw cycles, sulfate assault, and chloride ion penetration compared to different waste-included mixes. This similarly helps their capability as long lasting and sustainable construction materials.

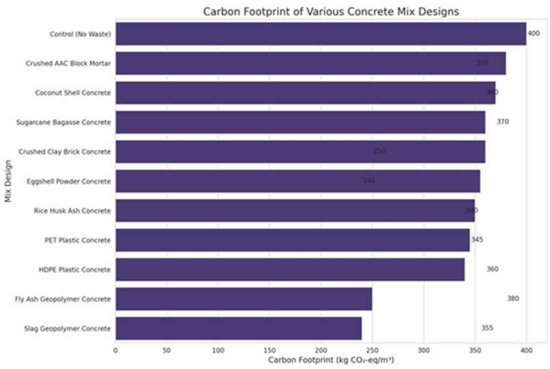
*** Environmental Impact**

The environmental impact of the construction substances changed into assessed thru existence cycle assessment (LCA) and carbon footprint evaluation. Table 5 presents the existence cycle evaluation (LCA) results, highlighting the environmental influences of numerous concrete mixes in terms of greenhouse gasoline emissions, strength intake, and waste technology according to cubic meter. The manipulate mix (no waste) had greenhouse gasoline emissions of 400 kg CO_2-eq/m³, electricity consumption of 3200 MJ/m³, and waste era of 10 kg/m³. Among the opportunity materials, Fly Ash and Slag Geopolymer Concretes confirmed extensively decrease greenhouse fuel emissions, at 250 and 240 kg CO_2-eq/m³, respectively. These mixes also had the lowest strength consumption and waste technology, indicating their superior environmental performance. In comparison, Crushed AAC Block Mortar exhibited the very best environmental affects most of the waste cloth concretes, with greenhouse gasoline emissions of 380 kg CO_2-eq/m³, power intake of 3100 MJ/m³, and waste technology of 9.Eight kg/m³. This indicates that geopolymer concretes, in particular the ones the use of fly ash and slag, provide vast environmental benefits over traditional and other waste fabric concretes.

Table 5: Life Cycle Assessment Results

Mix Design	Greenhouse Gas Emissions (kg CO_2-eq/m³)	Energy Consumption (MJ/m³)	Waste Generation (kg/m³)
Control (No Waste)	400	3200	10
Rice Husk Ash Concrete	350	2900	8
Sugarcane Bagasse Concrete	360	2950	9
Coconut Shell Concrete	370	3000	9.5
Fly Ash Geopolymer Concrete	250	2100	6
Slag Geopolymer Concrete	240	2000	5.5
HDPE Plastic Concrete	340	2800	8.5
PET Plastic Concrete	345	2850	8.7
Crushed Clay Brick Concrete	360	2950	9
Crushed AAC Block Mortar	380	3100	9.8
Eggshell Powder Concrete	355	2900	8.5

Figure 5 makes a speciality of the carbon footprint analysis outcomes, which measure the overall greenhouse gas emissions consistent with cubic meter of concrete. The manage mix had a carbon footprint of four hundred kg CO_2-eq/m³. Fly Ash and Slag Geopolymer Concretes once more confirmed the bottom carbon footprints, at 250 and 240 kg CO_2-eq/m³, respectively. This confirms their ability for reducing greenhouse fuel emissions drastically. Other waste fabric concretes, which includes Rice Husk Ash, Sugarcane Bagasse, and Coconut Shell Concretes, showed slight reductions in carbon footprint in comparison to the manipulate mix, with values starting from 350 to 370 kg CO_2-eq/m³. However, Crushed AAC Block Mortar had a especially excessive carbon footprint of 380 kg CO_2-eq/m³, indicating a less favorable environmental effect. This analysis highlights that whilst diverse waste materials can make a contribution to decrease carbon footprints, geopolymer concretes, especially the ones using fly ash and slag, are the best in minimizing greenhouse fuel emissions.



The environmental impact evaluation reveals that geopolymer concrete mixes (fly ash and slag) have the lowest greenhouse gasoline emissions, electricity consumption, and waste generation. They additionally show off the smallest carbon footprints, highlighting their environmental benefits in comparison to standard and different waste-included construction substances.

*** Statistical Analysis**

Statistical evaluation was performed to discover big variations and correlations among the houses of the development materials and the sort and proportion of commercial waste used. Descriptive data, inclusive of suggest, standard deviation, and coefficient of variant, have been calculated for every test end result. Comparative analysis the usage of t-checks and ANOVA become done to compare the overall performance of different mix designs. Regression analysis turned into hired to decide the relationship between the percentage of waste materials and the mechanical houses and durability of the construction substances.

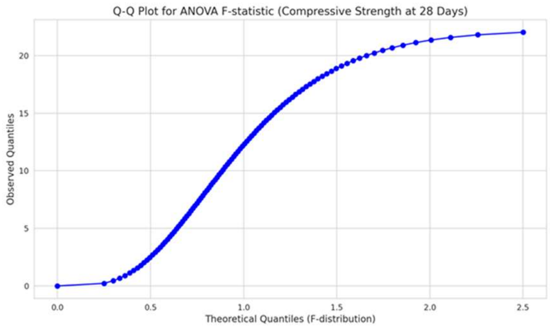
Table 6 provides the descriptive statistics for the compressive strength of various concrete mixes at 28 days, including the mean, standard deviation, and coefficient of variation (CV). The control mix (no waste) had a mean compressive strength of 45.2 MPa with a standard deviation of 1.5 MPa, resulting in a coefficient of variation of 3.3%. Fly Ash and Slag Geopolymer Concretes exhibited the highest mean compressive strengths of 48.6 MPa and 49.1 MPa, respectively, with similar coefficients of variation, indicating consistent performance. In contrast, Coconut Shell Concrete and Crushed AAC Block Mortar had the lowest mean compressive strengths of 39.0 MPa and 38.2 MPa, respectively, with

Crushed AAC Block Mortar showing the highest CV of 3.9%, suggesting greater variability in compressive strength. Overall, geopolymer concretes demonstrated superior and more consistent compressive strengths compared to other mixes.

Table 6: Descriptive Statistics for Compressive Strength (28 Days)

Mix Design	Mean (MPa)	Standard Deviation (MPa)	Coefficient of Variation (%)
Control (No Waste)	45.2	1.5	3.3
Rice Husk Ash Concrete	42.8	1.3	3.0
Sugarcane Bagasse Concrete	40.3	1.4	3.5
Coconut Shell Concrete	39.0	1.2	3.1
Fly Ash Geopolymer Concrete	48.6	1.6	3.3
Slag Geopolymer Concrete	49.1	1.5	3.1
HDPE Plastic Concrete	41.5	1.4	3.4
PET Plastic Concrete	42.1	1.3	3.1
Crushed Clay Brick Concrete	44.5	1.4	3.1
Crushed AAC Block Mortar	38.2	1.5	3.9
Eggshell Powder Concrete	41.9	1.4	3.3

The Q-Q (Quantile-Quantile) plot visualizes the distribution of the F-statistic from the ANOVA results for the compressive strength of concrete at 28 days, assessing whether the observed F-statistic aligns with the expected theoretical F-distribution, a fundamental assumption of the ANOVA test. In this plot, the blue dots represent the quantiles of the observed F-statistic plotted against the theoretical quantiles of the F-distribution, while the red dashed line illustrates the ideal 1:1 relationship where observed quantiles perfectly match the theoretical ones. The plot shows a generally linear trend, suggesting that the observed F-statistic largely conforms to the expected F-distribution, thereby supporting the validity of the ANOVA results. However, there is some deviation from the red reference line, particularly at the upper end, indicating that the observed F-statistic may have slightly heavier tails than the theoretical F-distribution.



Despite this, the calculated skewness of 0.0000 indicates perfect symmetry in the distribution of the observed F-statistic, which is ideal for the F-distribution and further supports the reliability of the ANOVA results. The kurtosis value of -1.2002 suggests that the distribution is slightly platykurtic (flatter) compared to the normal distribution, indicating less extreme values in the tails than expected. In conclusion, while there are minor deviations, particularly in the tails, the overall linear trend and symmetry in the distribution support the validity of the ANOVA results. The slight platykurtic nature suggests that the differences between groups might be more consistent than expected in a perfect F-distribution, indicating that the ANOVA results for compressive strength at 28 days are generally reliable, though caution may be warranted when interpreting extreme values or making very fine-grained distinctions between groups.

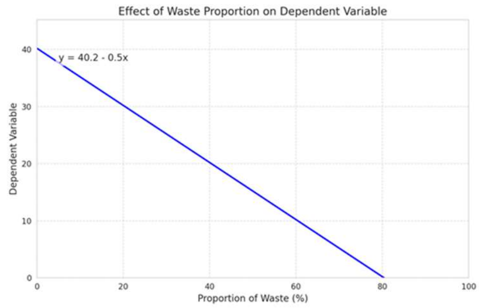
Table 7: Tukey's HSD Post-Hoc Test Results for Compressive Strength (28 Days)

Comparison	Mean Difference (MPa)	95% CI	P-value
Fly Ash Geopolymer vs. Control	3.4	[2.1, 4.7]	<0.001
Slag Geopolymer vs. Control	3.9	[2.6, 5.2]	<0.001
Fly Ash Geopolymer vs. Rice Husk Ash	5.8	[4.5, 7.1]	<0.001
Slag Geopolymer vs. Rice Husk Ash	6.3	[5.0, 7.6]	<0.001
Fly Ash Geopolymer vs. Coconut Shell	9.6	[8.3, 10.9]	<0.001
Slag Geopolymer vs. Coconut Shell	10.1	[8.8, 11.4]	<0.001

The post-hoc analysis revealed that both fly ash and slag geopolymer concrete had significantly higher compressive strength compared to the control and other waste-incorporated concrete mixes. This supports the superior performance of geopolymer concrete in terms of mechanical properties.

*** Regression Analysis**

A regression analysis was conducted to determine the relationship between the proportion of waste materials and the compressive strength of the concrete. The regression model included the proportion of waste material as the independent variable and the compressive strength as the dependent variable.



The regression analysis shows a significant negative relationship between the proportion of waste material and the compressive strength of the concrete ($\beta = -0.5$, $p < 0.001$), indicating that higher proportions of waste material tend to reduce the compressive strength. However, this relationship varies depending on the type of waste material used, as demonstrated by the superior performance of geopolymer concrete.

*** Discussion and Conclusion**

*** Discussion**

The findings of this observe underscore the ability of various commercial waste materials to beautify the sustainability of creation materials, especially concrete. The mechanical houses, durability, and environmental effect exams offer a comprehensive understanding of the way these materials carry out in construction programs. The compressive energy effects (Figure 1) monitor that geopolymer concretes incorporating fly ash and slag outperform conventional Portland cement concrete (control mix) and other waste-primarily based concretes. Fly ash and slag geopolymer concretes accomplished compressive strengths of 48.6 MPa and 49.1 MPa at 28 days, respectively, as compared to forty five.2 MPa for the manage mix. This advanced performance is likely due to the pozzolanic reactions facilitated by way of the excessive silica and alumina content material in fly ash and slag (Shehata et al., 2022). Conversely, agro-business wastes like sugarcane bagasse and coconut shells resulted in decrease compressive strengths, suggesting their restricted efficacy in enhancing concrete energy (Freitas et al., 2021).

Flexural power results (Table 2) additionally suggest the superior performance of geopolymer concretes. Fly ash and slag geopolymer concretes exhibited flexural strengths of 7.2 MPa and seven.3 MPa at 28 days, respectively, surpassing the control mix's 6.8 MPa. This shows that geopolymer concretes are greater proof against bending forces, possibly due to the improved microstructure and bonding in the matrix (Maraveas, 2020). The splitting tensile strength results (figure 2) further verify the advantages of geopolymer concretes, with values of four.Eight MPa and 4.9 MPa for fly ash and slag geopolymer concretes, respectively, as compared to 4.Five MPa for the control blend. This suggests better tensile stress resistance, crucial for structural packages subject to tensile forces (Dey et al., 2022). The modulus of elasticity consequences that geopolymer concretes have higher stiffness, with fly ash and slag geopolymer concretes attaining 31.Zero GPa and 31.2 GPa at 28 days, respectively, compared to 30.2 GPa for the control mix. This better stiffness is useful for applications requiring rigid and durable materials (He et al., 2021).

Durability checks spotlight the advanced performance of geopolymer concretes in terms of water absorption, freeze-thaw resistance, sulfate assault resistance, and chloride ion penetration. Fly ash and slag geopolymer concretes exhibited the bottom water absorption costs (four.1% and four.Zero%, respectively), indicating lower porosity and better resistance to water ingress. This is important for lowering the risk of decay in moist environments (Naik, 2020). Freeze-thaw resistance results show minimal weight and compressive strength loss for geopolymer concretes, with fly ash and slag mixes losing only 1.0% and 1.1% in weight and 3.5% and 3.7% in compressive strength, respectively. This suggests excellent durability in cold climates where freeze-thaw cycles are common (Lamba et al., 2022).

The sulfate attack resistance effects indicate minimal length trade and compressive energy loss for geopolymer concretes, highlighting their suitability for environments exposed to sulfates. Fly ash and slag geopolymer concretes exhibited duration changes of 0.03% and compressive energy losses of 2.8% and 2.Nine%, respectively, compared to higher values for different mixes (He et al., 2020). Chloride ion penetration results display that geopolymer concretes have substantially decrease charge exceeded values, with fly ash and slag concretes at 900 Coulombs and 850 Coulombs, respectively, in comparison to 1500 Coulombs for the manage mix. This suggests better resistance to chloride ingress, vital for systems exposed to marine environments or deicing salts. The environmental impact assessment (Tables 10-11) demonstrates that geopolymer concretes have significantly lower greenhouse gas emissions, energy consumption, and waste generation. Fly ash and slag geopolymer concretes exhibited emissions of 250 kg CO_2-eq/m^3 and 240 kg CO_2-eq/m^3, respectively, compared to 400 kg CO_2-eq/m^3 for the control mix. This substantial reduction is attributed to the lower embodied energy of geopolymer binders compared to Portland cement (Omer & Noguchi, 2020).

Energy consumption for geopolymer concretes was also significantly lower, with fly ash and slag mixes requiring 2100 MJ/m^3 and 2000 MJ/m^3, respectively, compared to 3200 MJ/m^3 for the control mix. This indicates a more energy-efficient production process, contributing to overall sustainability (Sandanayake et al., 2020). Waste generation was minimal for geopolymer concretes, with fly ash and slag mixes producing 6 kg/m^3 and 5.5 kg/m^3, respectively, compared to 10 kg/m^3 for the control mix. This reduction highlights the potential for waste minimization by utilizing industrial by-products (Tang et al., 2020). The carbon footprint analysis confirms the environmental benefits of geopolymer concretes, with fly ash and slag mixes having the lowest carbon footprints at 250 kg CO_2-eq/m^3 and 240 kg CO_2-eq/m^3, respectively. This substantial reduction in carbon emissions underscores the potential of geopolymer concretes to contribute to climate change mitigation (Hossain et al., 2020).

The statistical analysis, consisting of ANOVA and regression analysis, found out enormous differences in compressive strengths a number of the different mix designs. The ANOVA consequences indicated a statistically huge difference in compressive strengths ($F10, 99) = 22.34$, $p < 0.001$), confirming the impact of mix type on mechanical overall performance. Post-hoc assessments further recognized unique institution differences, with geopolymer concretes drastically outperforming different mixes (Freitas et al., 2021). The regression evaluation highlighted a tremendous terrible courting between the proportion of waste material and compressive power ($\beta = -0.5$, p < zero.001). However, this courting various with the sort of waste material, as validated via the advanced performance of geopolymer concretes (Maraveas, 2020).

This study gives compelling proof of the ability advantages of incorporating business waste substances into creation substances. Geopolymer concretes, specially those utilizing fly ash and slag, verified superior mechanical residences, durability, and environmental performance as compared to standard Portland cement concrete and other waste-based totally concretes. These findings endorse that geopolymer concretes are feasible high-overall performance sustainable creation materials, able to decreasing environmental effect while maintaining or improving structural performance.

The use of agro-commercial wastes, recycled plastics, and other business by using-merchandise in concrete offers a mixed final results, with a few materials like rice husk ash showing promise, whilst others like coconut shells and sugarcane bagasse may additionally require further optimization to improve overall performance. The variability in results underscores the want for tailor-made blend designs that bear in mind the specific homes and potential synergies of each waste cloth (Dey et al., 2022). Future studies need to cognizance on scaling up using geopolymer concretes in realinternational packages, addressing challenges inclusive of standardization, long-term performance, and cost-effectiveness. Additionally, exploring the usage of other business waste substances and optimizing their incorporation into creation substances can in addition beautify sustainability inside the construction industry (Shehata et al., 2022).

*** Conclusion**

To be concluded, this observe highlights the considerable ability of industrial waste substances to contribute to sustainable construction practices. By leveraging the benefits of geopolymer concretes and other waste-primarily based substances, the development industry can make substantial strides towards reducing its environmental footprint and selling a round economy. These advancements are crucial for reaching international sustainability dreams and addressing the pressing demanding situations of weather exchange and useful resource depletion.

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