Utilization of Recycled Aggregates in Fly Ash-Based Geopolymer Concrete for Pavement Construction

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Abstract:

The utilization of recycled aggregates in construction materials has garnered significant attention due to its environmental and economic benefits. This study investigates the feasibility of incorporating recycled concrete aggregates (RCA) as substitutes for natural aggregates in fly ash-based geopolymer concrete for pavement construction. This study investigates the utilization of recycled concrete aggregates (RCA) in geopolymer concrete for potential pavement applications. The performance of geopolymer concrete incorporating various levels of RCA (10%, 20%, 30%, and 40%) as replacements for natural aggregates was evaluated in terms of compressive strength, water absorption, abrasion resistance, and chloride ion permeability. The results showed that the compressive strength of geopolymer concrete decreased gradually as the RCA content increased, with mixes containing up to 20% RCA maintaining sufficient strength for pavement use. Water absorption and volume loss due to abrasion increased with higher RCA percentages, indicating greater porosity and reduced durability. The chloride ion permeability test revealed higher charge passage with increasing RCA content, suggesting increased permeability, but all mixes still exhibited low chloride ion permeability, indicating adequate resistance to chloride-induced corrosion. These findings demonstrate that while the use of RCA in geopolymer concrete can lead to a slight reduction in strength and durability, it remains a viable and sustainable option for pavement construction, especially when RCA replacement levels are kept below 20%.

Keywords: Compressive strength, Fly ash, Geopolymer concrete, Pavement, Recycled aggregates

1.Introduction

The utilization of recycled aggregates in fly ash-based geopolymer concrete is a forward-thinking approach to enhancing the sustainability of construction materials. As the construction industry faces increasing pressure to reduce its environmental footprint, traditional concrete, which relies heavily on natural aggregates and cement, has come under scrutiny due to its high resource consumption and significant carbon emissions. Fly ash-based geopolymers offer a promising alternative by utilizing industrial by-products like fly ash, which is a waste material from coal combustion, thus reducing the need for conventional cement. When combined with recycled aggregates—materials sourced from demolished concrete structures—geopolymer concrete not only mitigates the consumption of virgin resources but also contributes to the recycling of construction and demolition waste. This combination presents a dual environmental benefit: decreasing landfill waste and lowering the carbon impact of concrete production. The aim of this research is to explore the potential of fly ash-based geopolymer concrete with recycled aggregates in improving the performance and sustainability of construction materials, ultimately offering a more eco- friendly solution to the growing demand for durable, high-performance concrete.

Background and Motivation

The construction industry is one of the largest consumers of natural resources, which results in significant environmental impact, including high energy consumption and waste generation. As the demand for sustainable construction materials increases, the use of recycled aggregates, particularly recycled concrete aggregates (RCA), has emerged as a promising solution. Recycled concrete aggregates are derived from demolished concrete structures and can be used as a replacement for natural aggregates in new concrete production. Fly ash-based geopolymer concrete, which uses industrial waste by-products like fly ash as a binder, has gained attention as an eco-friendly alternative to traditional cement concrete. Incorporating RCA into geopolymer concrete offers both environmental and economic benefits, reducing landfill waste and conserving natural resources, while also providing potential cost savings in construction.

Need for sustainable solutions in pavement construction

Pavements are a critical part of global transportation infrastructure, with over 65 million kilometers of roads, highways, and urban streets worldwide. Traditionally, concrete and asphalt have been the main materials used for pavement construction. However, increasing concerns about greenhouse gas emissions, resource depletion, and inadequate waste management in the construction industry highlight the urgent need for more sustainable solutions. The production of traditional pavement materials, such as cement and aggregates, significantly contributes to carbon emissions, while the construction and renovation of pavements generates large amounts of waste, putting pressure on waste management systems. To address these challenges, integrating sustainability into pavement design, material selection, and construction methods is essential. Exploring alternative binders, industrial by-products, and recycled materials can lead to the development of more eco-friendly and resource-efficient pavements, helping to meet global sustainability goals.

Problem of Statement:

While the use of recycled concrete aggregates in conventional concrete has been explored, there is limited research on their application in fly ash-based geopolymer concrete, especially for pavement construction. The challenge lies in assessing the impact of varying levels of RCA on the mechanical properties, durability, and overall performance of geopolymer concrete. As the percentage of RCA increases, there is a concern that concrete's strength, durability, and long-term serviceability may be compromised, especially under environmental stresses like water absorption, abrasion, and chloride ion permeability.

Scope of this study

This study investigates the feasibility of incorporating RCA into fly ash-based geopolymer concrete for pavement applications. Specifically, the research focuses on the effects of replacing natural coarse aggregates with different percentages of RCA (10%, 20%, 30%, and 40%) on the concrete's compressive strength, water absorption, abrasion resistance, and chloride ion permeability. The study aims to determine the optimal RCA content that balances sustainability with performance requirements for pavement construction.

Objectives

- To evaluate the effect of varying RCA content (10%, 20%, 30%, and 40%) on the compressive strength of fly ash-based geopolymer concrete.
- To assess the impact of RCA on the water absorption and porosity of geopolymer concrete, which influences its durability.
- To investigate the abrasion resistance of geopolymer concrete with different RCA replacement levels to determine its suitability for pavements exposed to mechanical wear.
- To measure chloride ion permeability and evaluate the concrete's resistance to chloride-induced corrosion at various RCA replacement levels.
- To identify the optimal RCA replacement level (below 20%) for sustainable, durable, and high-performance geopolymer concrete for pavement applications.

2. Literature review

Geopolymer concrete represents an innovative class of alternative binders which utilize industrial by-products to completely eliminate ordinary portland cement content. The term "geopolymer" was first coined by Davidovits in 1979 to represent a broad range of alumino-silicate materials synthesized from geological or waste precursors (Davidovits, 1991). Geopolymer technology has recently garnered substantial attention as a sustainable substitute to conventional concretes owing to various advantageous credentials from a functional, economic and ecological standpoint (Provis and Bernal, 2014). This literature review offers a comprehensive overview of the fundamental concepts, synthesis processes, key benefits as well as current barriers and development scope concerning geopolymer concrete

Geopolymers comprise a family of inorganic alumino-silicate materials formed by alkali activation of aluminosilicate precursors like metakaolin, fly ash, slag etc. (Duxson et al., 2007). The amorphous to semi-crystalline three-dimensional silico-aluminate structures develop high early strength and stability. Geopolymerization involves exothermic reactions between the source material and alkaline solutions resulting in polymeric Si-O-Al-O bonds (Khale and Chaudhary, 2007). Tetrahedral SiO4 and AlO4 units randomly couple to yield sustainable cementitious binders without undergoing hydration. Varied Si: Al molar ratios determine the structure and properties.

The salient criteria for geopolymer synthesis include appropriate chemical composition and amorphous nature of the source materials, selection of suitable alkaline liquids, mixing proportions and curing conditions (Nath and Sarker, 2015). While class F fly ash containing silica and alumina remains widely explored as base precursor, alternate materials like GGBFS, rice husk ash and red mud are being examined. Combinations of multiple source materials also tailor the reactivity (Bernal et al., 2015). Alkaline solutions of sodium hydroxide or potassium hydroxide and sodium silicate aid dissolution. Superplasticizers prevent rapid setting. After mixing source, aggregates and alkaline liquid, geopolymer concrete undergoes heat curing which accelerates reaction kinetics and strength growth.

The use of industrial waste by-products like fly ash to replace cement makes geopolymer concrete a sustainable green construction material with 80-90% lower CO2 emissions (McLellan et al., 2011). The amorphous polymer structures formed provide high strength, superior chemical and thermal resistance compared to OPC products (Garcia-Lodeiro et al., 2015). Rapid strength development and facile fabrication are added advantages. The enhanced durability performance also circumvents premature deterioration issues commonly observed in conventional concretes. Thus, geopolymers offer functional, economic and ecological edge over traditional counterparts.

While the technology shows immense promise, some barriers have constrained widespread commercial adoption. Variable chemical composition of waste sourced materials causes inconsistent quality (Somna et al., 2011). Delayed setting time hampers productivity which needs intervention through additives. Lack of standards regarding appropriate mix design and curing impacts strength and reliability. Certain jurisdictions prohibit heat curing onsite which hinders projects. Limited understanding across industry sectors further restricts usage adoption, necessitating conclusive evidence regarding structural feasibility at pilot and field scale implementations.

3. Methodology

The utilization of recycled concrete aggregates (RCA) in geopolymer concrete, specifically fly ash-based geopolymer concrete (GPC), is a sustainable approach for pavement construction. This method offers the potential for reducing environmental impact by recycling construction waste while maintaining adequate performance for structural applications, such as pavements. Below is a detailed explanation of the methodology and mix design used in the study.

Geopolymer Concrete Preparation:

Geopolymer concrete is made by using an alkaline activator (commonly sodium hydroxide and sodium silicate) to activate fly ash. Fly ash is chosen as the primary binder because of its pozzolanic properties that allow it to react with the activator to form a strong cementitious material. In this study, recycled concrete aggregates (RCA) replace part of the natural coarse aggregates (VCA), with varying replacement percentages of 10%, 20%, 30%, and 40%.

Mix Design:

The mix design for fly ash-based geopolymer concrete is developed based on standard guidelines for geopolymer concrete, adjusted to the specific replacement levels of RCA. The proportion of fly ash to alkaline activator is critical in determining the strength and durability of the mix. Typically, the mix design is developed as follows:

- **Fly Ash Content**: 350-400 kg/m^3 (based on the required compressive strength).
- **Alkaline Activator ($NaOH + Na_2SiO_3$)**: 10-15% by weight of fly ash.
- **Water to Binder Ratio**: Around 0.4 to 0.45 for better workability and strength.

- **Coarse Aggregates (VCA + RCA)**: Proportions of natural coarse aggregates (VCA) and RCA are adjusted to evaluate their impact on the performance, with RCA replacing 10%, 20%, 30%, and 40% of VCA.

Curing and Testing:

The concrete mixes are subjected to standard curing conditions, typically at room temperature or in an oven at 60-80°C for accelerated curing. After curing, the samples are tested for various properties, including compressive strength, water absorption, abrasion resistance, and chloride ion permeability.

Material Selection and Preparation

- **Fly Ash (or Other Aluminosilicate Material):** Fly ash is the most common material used as a precursor in geopolymer concrete. It contains silica and alumina, which react with alkaline activators to form a strong binder. Class F fly ash is preferred due to its high reactivity and low calcium content, which results in better strength and durability.
- **Alkaline Activators (Sodium Hydroxide and Sodium Silicate):** Alkaline activators like sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) are essential to activate the fly ash in geopolymer concrete. These activators initiate the polymerization process. The right ratio of NaOH to Na_2SiO_3 is crucial for achieving the desired strength and workability of the mix.
- **Recycled Concrete Aggregates (RCA):** RCA is used to replace natural aggregates in the concrete mix. It’s a sustainable option that reduces waste and conserves natural resources. The quality of RCA is important—free from contaminants and with proper size distribution—to ensure it performs well in concrete.
- **Natural Coarse Aggregates (VCA):** Natural coarse aggregates (VCA) are used alongside RCA to maintain concrete's strength and bonding. These aggregates should be clean and well-graded to ensure good workability and strong interlocking with the geopolymer binder.
- **Fine Aggregates (Sand):** Fine aggregates fill the voids between coarse aggregates and improve the workability of the mix. They should be clean and free of impurities, with a proper grading to ensure a dense and durable concrete mix.
- **Water:** Water is necessary to activate the geopolymer binder. It should be clean and free of contaminants. The water-to-binder ratio is generally kept low (around 0.4-0.45) to improve concrete's strength and reduce porosity.
- **Additives and Chemical Admixtures:** Optional chemical admixtures, like plasticizers or retarders, can improve the workability and setting time of geopolymer concrete. Plasticizers help with workability without increasing water content, while retarders are used to delay setting in hot conditions.

Testing Procedures

- **Compressive Strength:** This is the ability of concrete to withstand compressive forces, typically measured at 7 and 28 days. It’s essential for ensuring that concrete can bear the loads applied in structural applications, such as pavements, without failure. Higher compressive strength generally indicates stronger, more durable concrete.
- **Water Absorption:** This test evaluates how much water the concrete can absorb, which is a direct indicator of its porosity and permeability. Higher water absorption means the concrete

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is more porous, making it more susceptible to environmental damage, such as freeze-thaw cycles or chemical attacks, which could reduce its durability over time.

- **Abrasion Resistance:** This measures the concrete's resistance to surface wear due to mechanical forces, such as friction from traffic or harsh weather conditions. Abrasion resistance is crucial for pavements and surfaces exposed to constant wear. A higher abrasion resistance ensures the surface will last longer under heavy usage.
- **Chloride Ion Permeability:** This test measures how easily chloride ions can penetrate the concrete, which is important for assessing the risk of corrosion in reinforced concrete. Chlorides, typically from de-icing salts or seawater, can cause steel reinforcement inside the concrete to corrode, weakening the structure. Concrete with low chloride ion permeability has better protection against such damage.

Physical and mechanical properties of recycled coarse aggregates

Recycled coarse aggregates (RCAs) are made by crushing old concrete. They tend to have irregular shapes, rough surfaces, and higher water absorption compared to natural aggregates. This can affect the strength and workability of concrete. RCAs are often less dense and have lower impact and abrasion resistance, which can reduce the durability of concrete. The grading and presence of contaminants like dust or metal can also influence the performance.

Table 1: Physical and mechanical properties of Virgin and Recycled aggregates

	Sp. Gravity	Density (kg/m^3)	Water absorption (%)	Aggregate Crushing Value (%)	Aggregate Impact Value (%)	Abrasion Value (%)
VCA	2.64	1542	3.75	27.2	26.78	24.3
RCA	2.51	1366	5.39	30.9	38.2	36.1

4. RESULTS AND DISCUSSION

The results of the study on geopolymer concrete with recycled concrete aggregates (RCA) reveal important insights into the performance and suitability of this material for pavement applications. Compressive strength decreased with increasing RCA content, with mixes containing up to 20% RCA maintaining adequate strength for structural use. Water absorption increased as the RCA percentage rose, indicating higher porosity and reduced durability against environmental exposure. Abrasion resistance followed a similar trend, with higher RCA content leading to increased volume loss due to wear. Chloride ion permeability also increased, suggesting a higher susceptibility to chloride-induced corrosion. Despite these trends, mixes with up to 20% RCA demonstrated acceptable performance, indicating that geopolymer concrete with moderate RCA replacement can still meet the required strength and durability for pavements.

Compressive strength

The compressive strength of geopolymer concrete refers to its ability to withstand compression or crushing forces. It is a critical property for evaluating the concrete's performance, particularly in structural applications.

Table 2: Compressive strength of geopolymer concrete

Replacement of RCA (%)	7 Days	28 Days
VCA (0% RCA)	38.5	40.2
RA10 (10% RCA)	36.5	37.5
RA20 (20% RCA)	34.5	36.0
RA30 (30% RCA)	33.0	34.0
RA40 (40% RCA)	32.0	33.5

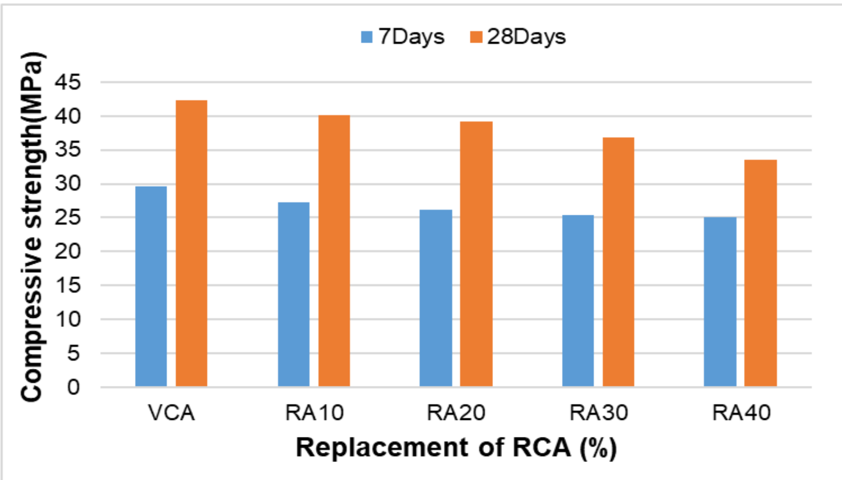

Figure 1: Compressive strength of RCA based Geopolymer concrete

The figure illustrates the compressive strength of geopolymer concrete at 7 and 28 days with varying percentages of recycled concrete aggregates (RCA) replacing natural coarse aggregates (VCA). It is evident that the compressive strength decreases gradually as the percentage of RCA increases. At 28 days, the strength ranges from approximately 40.2 MPa for 0% RCA (VCA) to around 33.5 MPa for 40% RCA (RA40). Similarly, at 7 days, the strength slightly drops with increased RCA content. However, the concrete mixes containing up to 20% RCA (RA10 and RA20) maintain reasonable strength values, suggesting they could be viable for applications such as pavements. This trend demonstrates that geopolymer concrete with RCA can still meet target strength requirements, especially at lower replacement levels.

Water absorption:

Geopolymer concrete mixes with varying proportions of recycled concrete aggregates (RCA) as substitutes for natural aggregates show water absorption patterns after 28 days of curing, to prevent RCA-based concrete's permeation qualities from being negatively affected, which could reduce its durability against environmental exposure during service life, it is important to evaluate sorptivity behaviour.

Table 3: water absorption data

Replacement of RCA (%)	7 Days (%)	28 Days (%)
VCA (0% RCA)	10	15
RA10 (10% RCA)	12	17
RA20 (20% RCA)	15	20
RA30 (30% RCA)	18	22
RA40 (40% RCA)	20	25

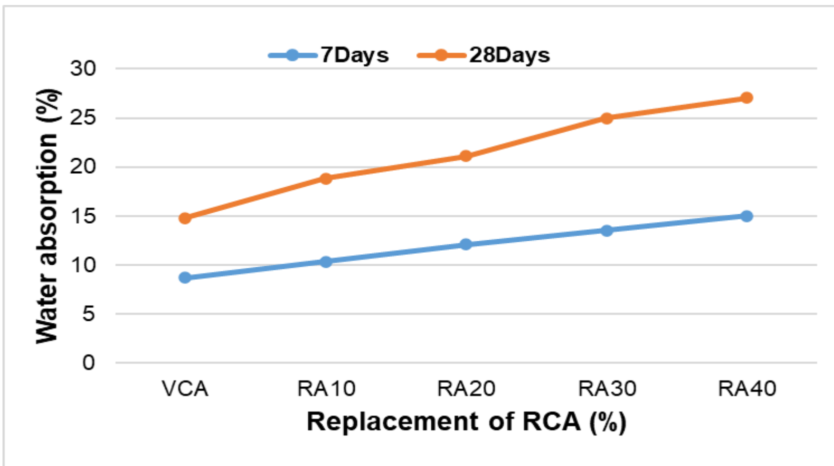

Figure 2: Water absorption of RCA based Geopolymer concrete

The figure shows the water absorption of geopolymer concrete at 7 and 28 days with varying percentages of recycled concrete aggregates (RCA) replacing natural coarse aggregates (VCA). As the percentage of RCA increases, the water absorption also increases for both 7 and 28 days. At 28 days, the water absorption reaches its highest for 40% RCA (RA40), approaching 25%, while it is lowest for the control mix (VCA), with values around 10%. At 7 days, the trend is similar but less pronounced, with values rising from approximately 5% for VCA to around 20% for RA40. This suggests that higher RCA content leads to greater porosity, which results in higher water absorption in the geopolymer concrete

Abrasion resistance of RCA-based geopolymer concrete:

The table abrasion resistance evaluated through weight loss in geopolymer concrete mixes incorporating increasing replacement percentages of natural aggregates via recycled concrete aggregates (RCA) after 28 days standard curing. Determining abrasion behavior is vital to assure surface integrity against progressive material disintegration from friction/impact damage during service life of concrete structures like pavements.

Table 4: water absorption data

Replacement of RCA (%)	Volume Loss at 7 Days ($cm^3/50cm^2$)	Volume Loss at 28 Days ($cm^3/50cm^2$)
VCA (0% RCA)	10	12
RA10 (10% RCA)	11	13
RA20 (20% RCA)	12	14
RA30 (30% RCA)	14	16
RA40 (40% RCA)	15	17

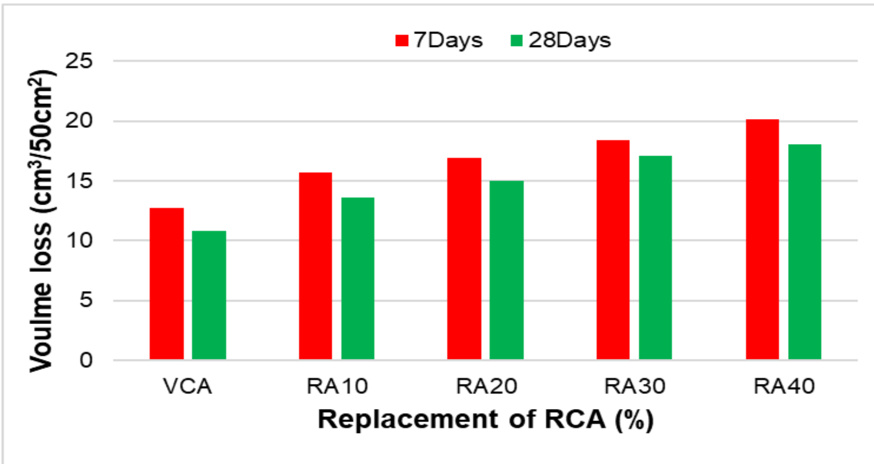

Figure 3: Abrasion resistance of RCA based Geopolymer concrete

The figure shows the abrasion resistance of geopolymer concrete at 7 and 28 days with varying percentages of recycled concrete aggregates (RCA). As the RCA percentage increases, the volume loss due to abrasion also increases, both at 7 and 28 days. The control mix (VCA) shows the lowest volume loss, while the mix with 40% RCA (RA40) exhibits the highest loss, indicating reduced abrasion resistance with higher RCA content

Chloride ion permeability of RCA-based geopolymer concrete:

Figure represents the resistance to chloride ion penetration assessed through total charge passed during accelerated migration testing in geopolymer concrete specimens with up to 40% coarse aggregates replaced via recycled concrete aggregates (RCA). Analyzing chloride diffusivity is imperative to evaluate durability against ingress of deleterious salts which can initiate rebar corrosion in structural reinforced concrete. It is discernible that charge passed, which serves as an index of chloride penetrability, rises progressively with increase in RCA replacement levels from 1687 coulombs for reference mix to 2196 coulombs for 40% RCA mix after 28 days standard moist curing. However, as per ASTM 1202 classification, all four concrete variations demonstrate low chloride ion permeability implying appreciable resistance against chloride ingress and corresponding corrosion risks.

Table 5: abrasion resistance of geopolymer concrete

Replacement of RCA (%)	7 Days (Coulombs)	28 Days (Coulombs)
VCA (0% RCA)	2500	2300
RA10 (10% RCA)	2700	2400
RA20 (20% RCA)	2800	2500
RA30 (30% RCA)	2900	2700
RA40 (40% RCA)	3200	3000

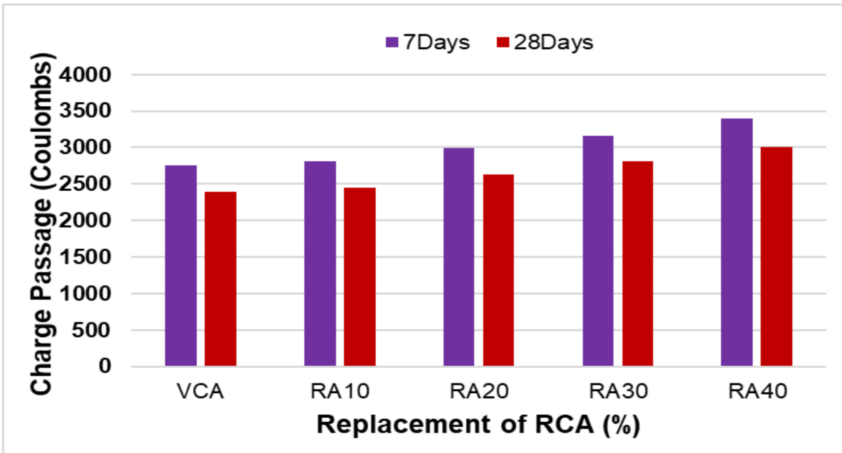

Figure 4: Chloride ions passage of RCA based Geopolymer concrete

The figure shows the chloride ion passage (measured in coulombs) of geopolymer concrete at 7 and 28 days with varying percentages of recycled concrete aggregates (RCA). As the RCA content increases, the charge passage also increases, indicating higher permeability. The control mix (VCA) exhibits the lowest charge passage, while the mix with 40% RCA (RA40) shows the highest, both at 7 and 28 days. This trend suggests that higher RCA replacement in geopolymer concrete leads to greater chloride ion permeability, which could impact the long-term durability of the concrete, especially in environments exposed to chloride-induced corrosion.

Conclusions:

Based on the results of various tests conducted on geopolymer concrete incorporating recycled concrete aggregates (RCA), the following conclusions can be drawn:

- **Compressive Strength:** As the percentage of RCA increases, the compressive strength of geopolymer concrete decreases. The compressive strength at 28 days ranged from 40.2 MPa for the control mix (VCA) to 33.5 MPa for the mix with 40% RCA (RA40). However, mixes with up to 20% RCA (RA10 and RA20) still met the target strength of 35 MPa required for M35 grade concrete, making them suitable for pavement applications.
- **Water Absorption:** Water absorption increased with higher RCA content. At 28 days, the water absorption ranged from 15% for VCA to 25% for RA40. This increase in water absorption indicates higher porosity, which may affect the durability of the concrete. Mixes

with higher RCA content should be considered for non-structural applications or where higher permeability is acceptable.

- **Abrasion Resistance:** The volume loss due to abrasion also increased with the RCA content. At 28 days, the volume loss ranged from 12 $cm^3/50cm^2$ for VCA to 17 $cm^3/50cm^2$ for RA40. This suggests that increasing RCA content reduces the abrasion resistance, which may impact the longevity of concrete used in high-wear environments like pavements.
- **Chloride Ion Permeability:** The chloride ion permeability increased with higher RCA content, as indicated by the charge passage. For 28 days, the charge passed ranged from 2300 coulombs for VCA to 3000 coulombs for RA40. Despite this increase, all mixes still exhibited low chloride ion permeability, implying adequate resistance to chloride ingress and reduced risks of corrosion.

In conclusion, geopolymer concrete incorporating up to 20% RCA can maintain acceptable compressive strength and performance for pavement construction, while mixes with higher RCA content show increased water absorption, volume loss, and chloride ion permeability, suggesting a reduction in durability. The use of RCA in geopolymer concrete offers an eco-friendly alternative, but careful control of the RCA percentage is necessary to ensure the concrete meets the required strength and durability standards for specific applications.

Future Scope:

Future research can explore the use of other types of recycled aggregates, such as glass or plastic, in geopolymer concrete. Long-term durability testing under extreme environmental conditions would also help understand how these mixes perform over time. Optimizing mix designs with higher RCA content and integrating more waste by-products could improve the sustainability and performance of geopolymer concrete. Additionally, studies could focus on the performance of geopolymer concrete in seismic zones or areas with heavy traffic. Life cycle assessments and cost analyses would also be valuable in evaluating the economic and environmental benefits of using geopolymer concrete in large-scale infrastructure projects.

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