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A CRITICAL REVIEW ON THE INFLUENCE OF FLY ASH, GGBS, CEMENT KILN DUST, WASTE PAPER PULP, AND RECYCLED AGGREGATES ON GEOPOLYMER CONCRETE PERFORMANCE

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ABSTRACT

Recent studies on geopolymer and mixed binder concretes using cement kiln dust (CKD), waste paper pulp (WPP), recycled coarse aggregate (RCA), and industrial byproducts fly ash and ground granulated blast-furnace slag (GGBS) are summarized in this study. The objective is to compile a summary of the way these materials affect mechanical behavior, fresh characteristics, water absorption, permeability, chloride/sulfate resistance, freeze-thaw, alkali-silica reactions, and flexural strengths, as well as durability. In comparison to single-binder mixtures, regulated replacement amounts of fly ash and GGBS often enhance long-term strength and durability, according to documented data. On the other hand, CKD and WPP may be used as partial replacements if pretreated or washed and proportioned appropriately. While alkali-activated binders may improve paste quality, RCA can impair density and early-age strength to some extent. Lack of defined mix-design methods for multi-waste geopolymer systems, uneven pre-treatment regimens for WPP and RCA, and little data on long-term field performance are important gaps. A harmonized experimental matrix and major test procedures are recommended at the conclusion of the study for future research to ensure reliable comparisons.

Keywords: Geopolymer concrete, GGBS, fly ash, waste paper pulp, recycled coarse aggregate, mechanical characteristics, and durability are all terms that come up while discussing this material.

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1. INTRODUCTION

Motivation: reduce CO_2 footprint of concrete by replacing Portland cement with industrial byproducts and reduce solid waste by valorizing paper mill sludge/pulp and construction-demolition waste (RCA).

Scope: this review focuses on how combinations of fly ash, GGBS, CKD, WPP and RCA affect workability, mechanical performance and durability of geopolymer or blended cement concretes. Representative reviews and experimental studies on waste paper/pulp in concrete are summarized below. [1]

This report summarizes recent research on geopolymer and mixed binder concretes that use recycled coarse aggregate (RCA), waste paper pulp (WPP), cement kiln dust (CKD), and industrial byproducts fly ash and ground granulated blast furnace slag (GGBS). A comprehensive review of the materials' effects on mechanical behavior, fresh properties, water absorption, permeability, chloride/sulfate resistance, freeze-thaw, alkali-silica reactions, flexural strengths, and durability is proposed. Recorded evidence suggests that, as compared to combinations consisting of a single binder, materials with controlled replacement proportions of fly ash and GGBS tend to exhibit improved long-term strength and durability. Conversely, CKD and WPP, when processed, rinsed, and proportioned properly, may be used as partial substitutes. Although binders activated by alkalis may enhance paste quality, RCA has the potential to reduce density and early-age strength. Important limitations include a lack of data on long-term field performance, inconsistent pre-treatment regimens for WPP and RCA, and a lack of specified mix-design procedures for multi-waste geopolymer systems. In order to make trustworthy comparisons in future studies, the authors suggest a standardized experimental matrix and key testing techniques.

Common names for this substance include geopolymer concrete, ground-granulated blast-furnace (GGBS), fly ash, recycled coarse aggregate, waste paper pulp, mechanical properties, and durability.

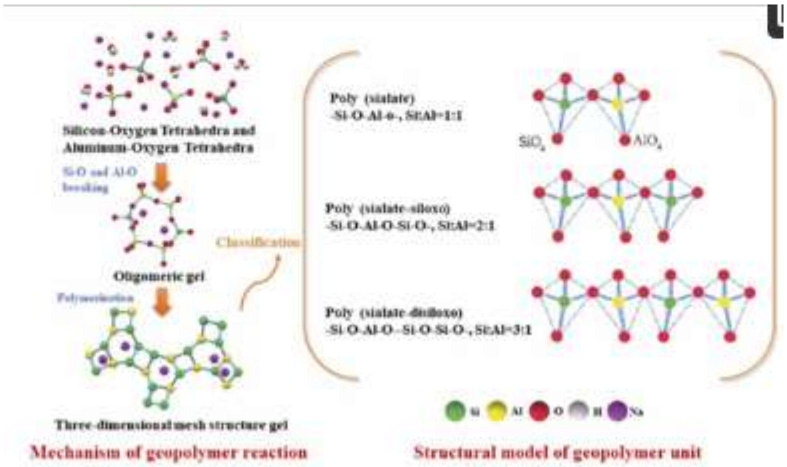

Figure 1. Mechanism of geopolymer reaction

1. 2. MATERIALS AND METHODS

The experimental investigation work is started with various tests on the constituent materials. The constituent materials are given below.

1. Cement
2. Fine Aggregates
3. Coarse Aggregates
4. Waste paper pulp
5. GGBS
6. Fly ash
7. Recycled coarse aggregate

Cement:

Ordinary Portland cement of 43 grades manufactured by Shree Ultratech Cement was used throughout the Experimental investigation. The quality of the cement was confirming to IS 8112:1989 was used in the field.

Fine Aggregate:

Fractions from 4.75 mm to 150 microns are termed as fine aggregate. Locally available river sand passed through 4.75mm IS sieve is applied as fine aggregate conforming to the requirements of IS 383:1970.

Coarse Aggregate:

Coarse aggregate shall be of hard broken stone of granite shall be of hard stone, free from dust, dirt and other foreign matters. The stone ballast shall be of 20mm and down and should me retained in 5mm square mesh and well graded

Fly ash: commonly used as a precursor in alkali-activated/geopolymer binders; improves workability and long-term strength when activated.

GGBS: reactive calcium source — when blended with fly ash, accelerates strength gain and refines pore structure.

Cement kiln dust (CKD): heterogeneous; can be used in small percentages as filler or partial cement replacement after characterisation due to variability in free lime and sulfates.

Waste paper pulp (WPP): paper-mill sludge/pulp ash or dried pulp has pozzolanic-like behaviour after calcination/ashing and can partially replace cement or fine aggregate; reports show potential improvement of insulating properties and acceptable strength at limited replacement levels (typically low percentages) but increases water absorption unless treated. (2)

Recycled coarse aggregate (RCA): reductions in density and early strength are common; pre-treatment (saturation, mechanical removal of adhered mortar) and increased paste/SCM content help recover strength and durability. [6]

Challenges of Geopolymer Concrete

Geopolymer concrete is an obvious solution to environmental problems caused by many different types of industry and the technology of the future for concrete [7]. Nevertheless, geopolymer concrete presents a number of obstacles during its development and manufacture. A number of interrelated factors govern the development of strength in geopolymer concrete. These include the type of precursor, the ratio of silica to alumina in the precursor material, the concentration and type of alkaline activator, the ratio of alkaline solution to precursor material, temperature during curing, and curing duration [8]. Despite the abundance of literature on these characteristics, fully comprehending the impact of their interaction is still an open question. The geopolymerization process is susceptible to changes in temperature, the alkaline activators have different formulations, and the binders have different chemical compositions, all of which contribute to this [9]. So, to get the most out of geopolymer concrete and make it last as long as possible, you need a more holistic strategy that takes into account the interplay of these factors. Another significant obstacle is the lack of readily available bulk aluminosilicates with consistent characteristics [10]. Commercial activators may be expensive and have a large impact on energy consumption, which is another reason why geopolymer concrete isn't used more often in building projects.

Problems with mixing, pouring, and completing the concrete on-site also arise from a number of other factors, such as the alkaline solution's caustic and dangerous character, which makes it difficult to handle [11], and the solution's viscosity, which makes it very sticky. On top of that, there isn't a lot of knowledge about using this technology among working engineers since there aren't enough standards and norms. On top of that, experts in the building business don't have enough practical training to fully profit from these materials.

1. 3. Mechanical properties :

Compressive strength: fly ash + GGBS blends in geopolymer/conventional mixes tend to give comparable or better 28–90 day strengths than OPC-only mixes due to continued pozzolanic reaction and denser microstructure. Low-to-moderate WPP replacement (often ≤10–20% by mass as ash or dried pulp) can be acceptable; unburned pulp in high amounts lowers strength. RCA typically reduces compressive strength by 10–30% depending on replacement ratio and RCA quality; alkali-activated binders and higher binder content mitigate losses. [12]

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Tensile & flexural: similar trends — reductions with high RCA or untreated WPP; improvements when GGBS is present due to denser matrix and better interfacial transition zone (ITZ).

Modulus & density: effective modulus decreases with WPP and RCA (lighter, more porous constituents).

4. Durability :

Water absorption / porosity: WPP and RCA often increase porosity; fly ash/GGBS reduce porosity over time by filling pores with C–(A)–S–H / geopolymeric gels. Pretreatment (ashing WPP, removing adhered mortar from RCA) improves performance. [4]

Chloride ingress and sulfate attack: well-activated fly ash/GGBS geopolymer matrices usually show superior chloride binding and sulfate resistance compared to plain OPC mixes, but CKD presence needs careful study because of free lime and sulfates.

Freeze–thaw and abrasion: more sensitive to increased porosity from WPP/RCA; air entrainment or reduced w/c (or equivalent in geopolymer) needed.

Alkali–silica reaction (ASR): RCA can carry reactive silica; combination with high-alkali activators needs careful assessment and mitigation.

II. REVIEW OF LITERATURE

With that history in mind, we conducted an experiment to see how various cement and sand replacement materials affected the concrete's qualities, taking into account both the kind and quantity of ingredients. The use of pozzolanic materials in concrete production and improvement has been the subject of much research. Study of relevant literature. The following sections provide information on the use of Ground Granulated Blast Furnace Slag (GGBS) and Rice Husk Ash (RHA) in concrete and their exposure to the environment.

Publication: 2014 by Deb, P. S., Nath, P., and Sarker, P. K. In 2015, Junaid, M. T., Kayali, O., Khennane, A., and Black, J. published: He used alkaline solutions of sodium silicates and hydroxide, as well as calcium class F flay ash, to determine the mix proportions of geopolymer concrete (GPC) in this research. Specifically, he found the optimal ratios of alkaline fluid to fly ash (AL/FA), water to geopolymer concrete (W/GPS), and alkaline fluid to water (AL/W) for the various mix designs.

Alkaline materials Sodium silicate ($Na2SiO3$) and Sodium Hydroxide (NaOH) were used as activators in geopolymer concrete, which Goriparthi, M. R., and TD, G. R. (2017) designed. The limiting ingredient was ground granulated blast furnace slag (GGBS). Also, we compared the results of OPC and geopolymer concrete, as well as the accompanying impacts of two concrete assessments (GPC20 and GPC50). Submersion in a 5% $H2SO4$ solution resolved significant limits of the corrosive mass loss factor (AMLF) and the strength characteristics (Compressive, Tensile, and Flexure).

The goal of MoslihAmerSalih (2014) was to create a high-strength mortar by activating GGBS with an alkali and palm oil fuel ash (POFA). The chemical composition of the geopolymeric binding phase was studied using TGA/DTG and DSC assays, while mechanical characteristics were evaluated using a compression test. Sodium silicate and sodium hydroxide were used to activate POFA at room temperature. The high strength geopolymer mortar that was created by combining 50% POFA and 50% GGBS demonstrated a compressive strength of 70 MPa after 28 days and 85 MPa after 90 days.

The impact of metakaolin on concrete properties was investigated in a 2017 study by Sunny AJagtap, Mohan N. Shirsath, and Sambhaji L. Karpe. Concerns about the environment are crucial to the long-term success of the concrete sector. A range of 5% to 25% cement substitution with glass powder, with a 5% gap in between, is to be investigated. The findings were compared with those of standard concrete after 7, 28, and 60 days of age using tests for compressive strength, split tensile strength, and flexural strength.

The aggregate of the test results indicates that Metakaolin has the potential to partially substitute cement in concrete.

This is the 2018 version of the paper by Saxena, Kumar, and Singh: He contrasted the compressive strength and durability tests conducted with sulphuric acid on geopolymer cement and regular portland cement in this article. He used alccofine powder, which has characteristics comparable to silica fume, in addition to fly ash, an alkaline solution (14M NaOH), and a silicate solution (Sodium silicate solution) to make the geopolymer cement. In the end, he came to the conclusion that, in terms of durability and compressive strength, this formulated blend (geopolymer mix) produced more dependable outcomes than OPC.

In 2019, Hadi, Zhang, and Parkinson published: Results from using OPC paste and a geopolymer concrete mix that he suggested were compared in this article. As a silicate source, he proposed using GGBFS and Class F fly ash (FA) in the mixture. In his suggested mix, he substituted the water-to-cement ratio with the following: SS/SH, Aw/Bi, and Al/Bi, the ratio of an alkaline solution to a binder. He came to the conclusion that the geopolymer paste he suggested performed better in the compressive strength, slump test, and setting time when the ratios of alkaline solution to binder (Al/Bi) were 0.5, sodium silicate solution to sodium hydroxide solution (SS/SH) was 2, Aw/Bi was 0.15, and 40% GGBS was added. It has been observed that cotton has better sunlight fastness than banana fiber. This could be because of the many insoluble substances and contaminants found in banana fiber, which are a kind of polymer. Several studies have examined the flexural plasticity of ferroconcrete beams reinforced with nylon fibers, but only a small number have addressed the impact of the fibers' problem on the beam's flexural plasticity and found that the plasticity indices rise as the fiber issue increases.

In their study titled "Effect of use of pulp ash on Strength of Concrete," Mr. U.R. Kawade et al. compared the chemical and physical properties of pulp ash with those of cement, and found that it could be partially substituted for a third, tenth, fifteenth, twenty-fiveth, or half an hour's worth of cement by weight. The findings demonstrate that the compressive strength of the POFA concrete was much greater than that of the non-POFA concrete. It has been shown that POFA may effectively substitute cement up to the maximum limit of V-J Day. V-J Day replacement was successful in achieving the optimal amount of POFA content. It is not necessary to use Super softener if you partially replace the cement with POFA; this will improve the workability of newly mixed concrete.

Researchers A.N. Danzigier and Z. Savir looked at how nylon fiber affected the flexural performance of high-strength concrete beams with a low longitudinal reinforcement magnitude relation. They found that, in comparison to beams with a minimum longitudinal reinforcement magnitude relation, the beams with nylon fiber added were crispier. The strength and hardness of concrete may be enhanced by using hybrid fibers of different kinds and sizes, as opposed to nylon fibers. This kind of fiber can play a variety of helpful effects at different levels of the hybrid process. Nevertheless, there is a dearth of literature on the subject of flexural performance in RC beams reinforced with hybrid fibers.

An Experimental Study on the Characteristics of Silica Fumes as a Modest Alternative to Cement was Conducted by Sasikumar and Tamilvanan. M30 grade concrete with varying percentages of cement and silica fume replaced is the primary focus of this research. As the amount of silica fume rises from 0% to 25%, the typical consistency increases by around 40%. At a replacement level of 25% silica fume, the material achieved its maximum compressive strength after 7 and 28 days. Using 25% silica fume as a cement substitute also results in a high split tensile strength.

Bhadra & Ghutke Investigate the Effects of Silica Fume on Concrete. According to the findings, silica fume is an improved alternative to cement. Concrete made with silica fume increases in strength at a rapid pace. Adding more silica fume to concrete reduces its workability. Using 10% silica fume as a substitute yields the best compressive strength rating. Because regular concrete loses strength when cement is replaced with silica fume at a rate of 15%. A replacement level of 10% to 15% silica fume is considered optimal.

3. Typical experimental matrix

Design mixes to systematically vary one parameter at a time while keeping others constant:

Baseline (control): OPC concrete (or single-source geopolymer) with natural aggregates.

Factor 1 — Binder blends (replace cement with/activate): 0% (control), 20% FA, 40% FA, 30% FA + 20% GGBS, 50% GGBS blends, CKD at 5% & 10% substitution.

Factor 2 — Waste paper pulp (as dried pulp or ash): 0%, 5%, 10%, 15% (as partial cement replacement by mass) — include both raw pulp and calcined/ashed pulp variants.

Factor 3 — RCA replacement (by volume or mass of coarse aggregate): 0% (natural), 25%, 50%, 100% RCA. Suggested replication: at least 3 specimens per test age. Ages: 7, 28, 56, 90 days (and longer if possible).

4. Recommended tests & standards

Fresh: slump/flow, unit weight, air content.

Mechanical: compressive strength split tensile, flexural, modulus of elasticity.

Durability: water absorption, sorptivity, rapid chloride permeability test (RCPT) / migration test, chloride profile sulfate immersion, accelerated carbonation, freeze–thaw cycles, acid resistance (if relevant). Microstructure: SEM, XRD, TGA/DTG, pore-size (MIP). For RCA / **WPP:** characterize particle size distribution, organic content, loss on ignition (LOI), specific gravity, and water absorption. Include leachate/toxicity tests if CKD or industrial wastes are used.

5. Expected results & interpretation guidance

Combining FA + GGBS with appropriate alkali activator or Portland supplement generally improves long-term strength and durability via denser matrix and better ITZ.

WPP gives best results when processed (dried, sieved, possibly calcined to ash); unprocessed pulp raises water demand and porosity. Typical beneficial replacement levels reported are low (often ≤10–15%), but exact optimum depends on WPP processing.[4]

RCA performance strongly depends on source quality: high adhered-mortar content increases porosity; pre-wetting and higher binder content help.

CKD is variable; small additions can be tolerated, but chemical characterization (free lime, sulfates, chlorides) is essential before prescribing replacement levels.

6. Research gaps & recommendations

1. Standardised pre-treatment and characterization protocols for waste paper pulp (raw vs ash) — many papers use different procedures making cross-study comparison difficult.[2]
2. Lack of long-term field trials: most studies are laboratory-scale; service-life modelling and field exposure data are scarce.
3. Combined multi-waste geopolymer systems (FA+GGBS+CKD+WPP+RCA) are under-studied optimization frameworks and mix design guidelines are needed.
4. Environmental and leachability studies for CKD + WPP blends to ensure no secondary pollution pathways.
5. Life-cycle assessment (LCA) and techno-economic analysis comparing multi-waste geopolymer mixes vs OPC-based mixes.

7. Conclusions

This review article highlights the latest research findings on geopolymer pavement-quality concrete. Special attention is given to the discussion of material properties that are relevant to the performance of concrete pavements. Based on the comprehensive review, the following are the conclusions.

The quality of precursor materials is crucial in achieving the desired properties for geopolymer pavement-quality concrete. Most studies in the past focused on the use of fly ash and GGBFS as precursor materials, and very few studies have explored other industrial and agricultural wastes. It shows that other precursors have potential in the application of geopolymer pavement-quality concrete. It is important to carefully assess the physical and chemical characteristics of precursor materials to ascertain their application in geopolymer pavement-quality concrete. The exploration of locally available precursor materials can reduce the carbon footprint of geopolymer concrete pavements and thereby achieve the sustainable development goals in the pavement industry.

The strength properties of geopolymer concrete were found to be superior and meet the requirements of geopolymer pavement-quality concrete. However, attention should be given to the optimum proportion of precursors and alkaline solution in the mix design process.

The modulus of elasticity of geopolymer concrete shows variability when compared to conventional Portland cement concrete. Several factors, such as precursor materials, concentration of alkaline activators, and curing conditions, influence the elastic modulus of geopolymer concrete. Moreover, ambient curing can produce a desirable elastic modulus for geopolymer pavement-quality concrete and therefore show practical viability in construction.

The drying shrinkage of geopolymer concrete was found to be lower than that of the conventional Portland cement concrete, and similar trends were observed for the coefficient of thermal expansion. The reduction in the coefficient of thermal expansion of the geopolymer concrete will positively contribute towards the long-term performance of concrete pavements.

The durability of geopolymer concrete with respect to resistance to abrasion and freeze–thaw resistance was found to be excellent and was attributed to the formation of dense binding phases such as sodium alumina silicate hydrate and calcium alumina silicate hydrate in the hardened geopolymer concrete.

9. Future Recommendations

Future studies should focus on evaluating properties of geopolymer concrete relevant to the performance of concrete pavement. Pertinent properties such as elastic modulus, coefficient of thermal expansion, drying shrinkage, and thermal conductivity should be determined.

The potential of locally available industrial and agricultural waste should be studied for its use as precursor material in geopolymer pavement-quality concrete.

Emphasis should be given to developing alternative activators derived from waste materials to reduce cost and improve the energy efficiency of geopolymer pavement-quality concrete.

There is significant scope to understand the effect of recycled aggregates in geopolymer concrete and further evaluate its pertinent properties for pavement application.

Studies can also be carried out to evaluate the field performance of geopolymer pavement-quality concrete and ascertain its optimum design for resilient concrete pavement in the context of extreme global climate change.

Research shows the environmental benefits of various precursors in construction materials and there is great scope to explore their benefits in geopolymer pavement-quality concrete.

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