

Numerical Analytical Investigation Of CMCS

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ABSTRACT – The present study investigates the effect of ceramic matrix reinforcement on the compressive strength and structural behavior of geopolymer concrete through an experimental and numerical analytical approach. Alumina powder was selected as the ceramic reinforcing material because of its high hardness, dense particle structure, and superior resistance to deformation. M40 grade geopolymer concrete was prepared as the control mix, while ceramic reinforced specimens were developed by incorporating alumina powder as a partial replacement of fly ash binder at 7% and 8% proportions.

Standard concrete cube specimens were cast, cured for 7 days and 28 days, and tested under compressive loading using Universal Testing Machine. The ultimate failure loads obtained during testing were converted into compressive strength values and compared analytically with the control concrete. The results showed that the addition of alumina powder improved the compressive resistance of geopolymer concrete by enhancing matrix compactness and reducing internal voids.

Among the selected replacement levels, the specimen containing 7% alumina powder exhibited the highest compressive strength and the maximum percentage increase over the control mix, while the 8% replacement also showed improvement but with comparatively lower performance. This indicates that moderate ceramic inclusion provides better stress transfer and crack resistance within the geopolymer matrix.

The study concludes that controlled addition of alumina powder is an effective method for improving the structural performance and compressive strength of geopolymer concrete, and 7% ceramic replacement was found to be the optimum proportion for the present investigation.

Key Words: Ceramic Matrix Composite, Alumina Powder, Geopolymer Concrete, Concrete Mix, Compressive Strength, Numerical Analysis, Ceramic Reinforcement, Structural Behaviour.

1.INTRODUCTION

In recent years, there has been a growing demand for advanced construction materials that can provide higher strength, improved durability, and better resistance to structural failure. Among such materials, Ceramic Matrix Composites (CMCs) have gained significant importance due to their excellent hardness, high compressive resistance, thermal stability, and resistance to abrasion. The incorporation of ceramic materials into conventional concrete matrices has shown considerable

potential in enhancing the overall mechanical performance of

composite systems.

Ceramic materials are known for their dense particle arrangement and rigid internal bonding characteristics. When introduced into a concrete binder matrix, these materials help in reducing internal voids, improving compactness, and increasing the ability of the concrete to resist compressive stresses. Because of these properties, ceramic reinforcement is now being considered as an effective method for the development of high-performance concrete composites.

Geopolymer concrete, prepared using fly ash and alkaline activators, has emerged as a suitable alternative to conventional cement concrete due to its good strength and durability characteristics. However, under heavy loading conditions, internal pores and brittle cracking may still affect its structural efficiency. To overcome this limitation, the addition of ceramic reinforcing particles can improve the density and crack resistance of the concrete matrix.

Among the available ceramic materials, alumina powder is considered highly effective because of its superior hardness, chemical stability, and fine particle size. Its inclusion in geopolymer concrete can improve matrix packing and contribute to higher compressive strength. Therefore, the present study focuses on the numerical analytical investigation of ceramic matrix reinforced geopolymer concrete by incorporating alumina powder as a partial replacement of fly ash binder at 7% and 8% levels. The concrete specimens were cast, cured, and tested under compressive loading to evaluate the effectiveness of ceramic reinforcement on structural performance.

2.SIGNIFICANCE OF THE STUDY

The present investigation holds significant importance in the field of advanced concrete technology because it focuses on improving the mechanical performance of geopolymer concrete through ceramic matrix reinforcement. Conventional concrete, although widely used in structural applications, often suffers from internal voids, brittle cracking, and limited resistance under high compressive loading. Therefore, there is a continuous need for developing stronger and denser composite materials capable of offering better structural stability and durability.

Ceramic Matrix Composites are known for their high hardness, dense particle structure, and superior resistance to deformation. The incorporation of ceramic materials into a concrete binder

matrix can improve compactness, reduce internal pore spaces, and enhance the transfer of stresses under loading. This makes

ceramic reinforcement an effective approach for increasing the compressive strength and crack resistance of concrete composites.

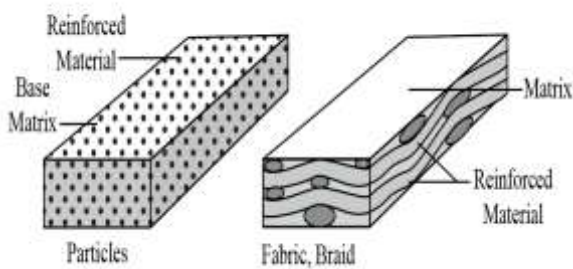


Figure1.1: Mechanical Behaviour of Composite Material

In the present study, alumina powder has been used as the ceramic reinforcing material because of its excellent hardness, chemical stability, and micro-filler characteristics. The addition of alumina powder in geopolymers concrete is expected to produce a denser matrix and improve the overall load carrying capacity of the concrete specimens. Such improvement is highly beneficial for the development of high-performance structural materials used in buildings, pavements, precast units, and other heavy load bearing components.

Thus, the significance of the present work lies in establishing ceramic reinforced geopolymer concrete as a practical and effective construction material capable of providing enhanced strength, improved durability, and better resistance against structural failure.

3.LITERATURE SURVEY

Ceramic Matrix Composites (CMCs) have emerged as one of the most promising advanced engineering materials due to their exceptional thermal stability, superior hardness, low density, oxidation resistance, and improved fracture toughness when compared with conventional monolithic ceramics. Researchers across the globe have extensively investigated their structural response, mechanical durability, thermo-mechanical behavior, machining characteristics, and reinforcement capability for high-performance applications. The present literature survey reviews significant prior studies directly associated with numerical, analytical, and experimental investigation of ceramic matrix composites while excluding artificial intelligence and computer-based prediction studies as per the present research scope.

Goda conducted an important numerical modeling study on ceramic/composite targets subjected to ballistic impact and evaluated the influence of cohesive material parameters on the deformation and energy absorption mechanism [1]. Using explicit finite element formulations, the author demonstrated that ceramic layers significantly improved impact resistance and controlled crack propagation when properly bonded with backing composite material. The study confirmed that numerical analytical models can effectively estimate ceramic failure under severe loading conditions.

Zhao, Tu, and Mao investigated the thermo-mechanical film cooling performance of braided ceramic matrix composite plates containing preformed holes [2]. Their research numerically examined thermal gradients developed around ceramic matrix structures and reported that the thermal conductivity and internal fiber arrangement of ceramic composites strongly govern heat dissipation. The study highlighted that CMCs can withstand aggressive thermal exposure while maintaining structural integrity, making them highly suitable for elevated temperature engineering fields.

Bai Cheng and Ye Ding performed both theoretical and experimental investigations on SiC/SiC ceramic matrix composites subjected to laser water jet machining [3]. Their observations showed that although ceramic matrix composites exhibit high hardness and brittleness, the internal fiber reinforcement restricts catastrophic crack spread and improves dimensional retention during machining. This work was significant in understanding the interaction between ceramic reinforcement and external stress concentration.

Guangwu Fang presented a broad review on ceramic matrix composites and environmental barrier coatings for aero-engine applications [4]. The author discussed material development, oxidation resistance, high-temperature performance, and failure mechanisms of ceramic composites. It was concluded that alumina and silicon carbide based ceramic composites possess superior thermal shock resistance and maintain mechanical stability under cyclic temperature conditions. This study established that ceramic reinforcement systems are increasingly replacing metallic counterparts in critical structural zones.

Michele Ferraiuolo investigated the thermo-mechanical behavior of ceramic matrix composite wing leading edges through sub-model numerical analyses [5]. The study revealed that ceramic composites show remarkable dimensional stability, low thermal deformation, and controlled internal stress redistribution under combined thermal and aerodynamic loading. The findings further emphasized the reliability of numerical simulation methods in predicting service behavior of CMC structures.

Promakhov and Vorozhtsov studied the dynamic behavior of ceramic matrix composites obtained through additive technologies [6]. Their research focused on load transfer, deformation evolution, and fracture initiation under dynamic impact conditions. Results demonstrated that the ceramic matrix acts as a rigid load-bearing medium while reinforcing constituents contribute to crack arresting behavior. This significantly improves the toughness and impact survivability of the composite system.

Hongbo Lu and Yancheng Liu conducted an experimental and numerical study on the tensile behavior of three-dimensional woven ceramic composites [7]. Their work revealed that the woven reinforcement architecture within the ceramic matrix distributes tensile stress more uniformly and delays brittle failure. Progressive damage analysis further indicated that fiber bridging and matrix confinement are responsible for improved post-cracking resistance. Such studies are valuable in understanding how ceramic matrix composites sustain mechanical loads beyond elastic limits.

Rajesh S. Kumar performed numerical predictions and experiments on delamination failure in ceramic matrix composites [8]. The research concluded that interfacial bonding between matrix and reinforcement plays a decisive role in resisting crack extension. Cohesive zone modeling successfully predicted the initiation and propagation of delamination, thereby validating the suitability of numerical analytical approaches in fracture characterization of ceramic systems.

Peng Lina and He Guoqiang investigated active cooling ceramic matrix composites for ramjet propulsion systems [9]. Under very high thermal flux, ceramic matrix composite panels exhibited superior heat shielding capacity with controlled thermal penetration. Their numerical transient heat transfer simulations showed that ceramic composite structures can sustain temperatures exceeding conventional material limits without major structural degradation. This demonstrates the potential of ceramic composites in thermal barrier and refractory applications.

Olawale Monsur Sanusi and Olatunde Ajani Oyelaran studied ceramic/steel composite systems for structural applications using numerical and experimental approaches [10]. Although the reinforcement combination differed, the study provided direct evidence that alumina ceramic layers substantially improve compressive resistance, impact absorption, and localized deformation control. Their work supports the broader understanding that ceramic constituents enhance stiffness and compressive load transfer efficiency.

Unsel, Goller, and Koch reviewed principles and approaches for machining simulation of ceramic matrix composites at microscale [11]. The authors noted that the heterogeneous nature of ceramic composites causes non-uniform stress concentration, but due to internal reinforcement and matrix hardness, the material demonstrates strong wear resistance and dimensional stability. Their work also emphasized that numerical modeling is essential for evaluating microscale crack initiation in brittle ceramic domains.

Huiyun Zhang and Zhigang Zhao reviewed abrasive machining technology of SiC ceramic composites [12]. The paper reported that ceramic composites possess superior abrasion resistance but their machining response depends largely on matrix density, reinforcement orientation, and interfacial bonding. The research offered strong evidence regarding the mechanical robustness of silicon-based ceramic systems under frictional and compressive forces.

Vishal Kumar, Hitesh Vasudev, and Neeraj Kumar presented a comprehensive review on ceramic matrix composites for defense applications [13]. Their study summarized that ceramic composites exhibit high specific strength, enhanced fracture resistance, and excellent penetration resistance owing to the synergistic action of ceramic hardness and internal reinforcement continuity. Such findings support the use of ceramic particulates like alumina and silicon carbide in load-bearing cementitious matrices.

N. Radhika and M. Sathish reviewed silicon-based ceramic matrix composites and infiltration-based manufacturing techniques [14]. Their analysis indicated that proper infiltration and densification significantly enhance matrix compactness,

reduce porosity, and improve compressive strength. The study is particularly relevant because mechanical properties of ceramic reinforced composites are strongly dependent upon the homogeneity of matrix filling and particle distribution.

Bulut Berk and Ramazan Karakuzu experimentally and numerically investigated ballistic performance of advanced composites with ceramic dominated phases [15]. Their study again reinforced the understanding that ceramic materials exhibit superior energy dissipation, localized crack control, and compressive resistance under sudden high loading.

From the above literature, it is clearly observed that most previous researchers have concentrated on thermal analysis, ballistic resistance, fracture mechanics, tensile response, machining behavior, and delamination studies of ceramic

matrix composites under numerical and experimental frameworks. However, very limited work has been reported on the direct utilization of ceramic materials such as alumina or silicon-based ceramic constituents as partial reinforcement in concrete matrices for evaluating compressive strength enhancement through numerical analytical interpretation. In addition, only a few studies correlate theoretical mix proportioning, material replacement percentage, and practical compressive testing behavior into one integrated structural investigation. Therefore, the present study focuses on bridging this gap by performing a numerical analytical investigation of ceramic matrix composite reinforced concrete specimens with specific replacement percentages and evaluating their compressive performance through analytical calculations and practical validation.

4. RESEARCH GAP & PROBLEM STATEMENT

4.1 Aim

The aim of the present study is to investigate the effect of ceramic matrix reinforcement on the compressive strength and structural behavior of geopolymer concrete by incorporating alumina powder as a partial replacement of fly ash binder and to evaluate its performance through experimental testing and numerical analytical comparison.

4.2 Research Gap

From the review of previous literature, it was observed that Ceramic Matrix Composites have been widely investigated for their mechanical strength, thermal resistance, fracture behavior, and industrial applications. Many researchers have studied ceramic composites in aerospace, defense, and high-temperature engineering fields. However, comparatively limited work has been carried out on the practical use of ceramic materials as reinforcing additives in geopolymer concrete for improving compressive strength and structural compactness.

In particular, the utilization of alumina powder as a ceramic matrix reinforcing constituent in fly ash based geopolymer concrete has not been sufficiently explored through direct casting and compressive testing methods. Also, only limited studies are available regarding the identification of an optimum ceramic replacement percentage capable of producing

maximum structural benefit without causing brittleness. This creates a need for a focused experimental and analytical investigation in this area.

4.3 Problem Statement

Although geopolymer concrete offers better durability and environmental advantages compared to conventional concrete, it may still contain internal pores and exhibit brittle cracking under high compressive loading. The challenge therefore lies in improving its internal matrix compactness and load carrying capacity without disturbing the practical casting process.

Ceramic materials such as alumina powder possess high hardness, dense particle characteristics, and strong resistance to deformation, which indicate their potential as reinforcing additives in geopolymer concrete. However, the exact effect of controlled alumina powder inclusion on compressive strength improvement and structural behavior has not been clearly established. Hence, the present study addresses this problem by experimentally investigating ceramic reinforced geopolymer concrete and analytically determining the optimum replacement percentage for enhanced compressive performance.

5. METHODOLOGY

5.1 Research Design

The present research was designed to investigate the influence of ceramic matrix reinforcement on the compressive performance of geopolymer concrete through an analytical and experimental approach. The study was primarily focused on evaluating how the addition of alumina based ceramic material affects the internal density, load transfer mechanism, and ultimate compressive strength of concrete composites. For this purpose, a systematic methodology was adopted involving material selection, mix proportioning, preparation of reinforced concrete specimens, curing, compressive strength testing, and numerical analytical interpretation of the obtained results.

Initially, an extensive review of previous studies related to ceramic matrix composites, ceramic fillers, and composite concrete behavior was carried out to understand the mechanical significance of ceramic reinforcement in brittle matrix systems. Based on this understanding, alumina powder was selected as the ceramic reinforcing material because of its superior hardness, chemical stability, thermal resistance, and micro-filler characteristics. Thereafter, M40 grade geopolymer concrete was designed as the control matrix and comparative specimens were prepared by incorporating ceramic alumina powder at selected replacement levels. The final objective of the research design was to establish a direct comparison between conventional geopolymer concrete and ceramic reinforced geopolymer concrete through practical testing and analytical evaluation.

5.2 Selection of Constituent Materials

The effectiveness of ceramic reinforced composite concrete depends largely on the quality and compatibility of the constituent materials used in the preparation of the specimens.

In the present work, Class F fly ash was selected as the primary binder material due to its pozzolanic properties and suitability for geopolymer concrete production. Fine aggregate conforming to Zone II grading was used to ensure proper particle packing and adequate bonding with the binder matrix. Crushed coarse aggregate of 20 mm nominal size was selected to provide the primary skeletal strength and interlocking resistance within the concrete.

Sodium hydroxide and sodium silicate solutions were used as alkaline activators for initiating the geopolymeric reaction within the fly ash binder. In addition to these conventional constituents, alumina powder was selected as the ceramic matrix reinforcement material. Alumina powder is chemically represented as Al_2O_3 and is widely recognized for its high hardness, superior abrasion resistance, excellent thermal stability, and dense particle characteristics. Due to its very fine particle size, alumina powder has the ability to fill micro-voids inside the binder matrix and improve the compactness of concrete. In the present study, alumina powder was incorporated as a partial replacement of fly ash in order to evaluate its contribution towards compressive strength enhancement and crack resistance.

5.3 Mix Design of M40 Grade Geopolymer Concrete

The concrete mix used for the present investigation was designed for M40 grade geopolymer concrete in accordance with IS 10262:2009 and IS 456:2000 provisions. The characteristic compressive strength required at 28 days was taken as 40 MPa under severe exposure conditions. To account for normal variations in production and testing, target mean strength was determined by using the standard expression:

$$f_{target} = f_{ck} + 1.65S$$

where,

f_{target} = target mean strength,

f_{ck} = characteristic compressive strength,

S = standard deviation.

For M40 grade concrete with good quality control, the standard deviation was considered as 5 MPa. Therefore,

$$\text{Target mean strength} = 40 + (1.65 \times 5) = 48.25 \text{ MPa.}$$

The water to binder ratio was selected as 0.40, which satisfies the durability requirement for severe exposure conditions. The maximum water content for 20 mm aggregate was taken as 186 litres and adjusted to 197 litres for desired workability. The binder content was calculated as:

$$\text{Binder Content} = \frac{197}{0.40} = 492.5 \text{ kg/m}^3$$

Since this value was greater than the minimum required binder quantity, the mix was considered acceptable. Based on standard aggregate proportioning, the volume fraction of coarse aggregate was taken as 0.56 and fine aggregate as 0.44. The total quantities of fly ash, fine aggregate, coarse aggregate, and alkaline solution were then determined for one cubic meter of

geopolymer concrete. This control mix proportion was used as the base mix for further ceramic reinforcement replacement.

5.4 Preparation of Ceramic Reinforced Composite Mix

After the control mix design was finalized, ceramic reinforcement was introduced into the geopolymer concrete in the form of alumina powder. The alumina powder was added as a partial replacement of fly ash binder at two different proportions, namely 7% and 8% by weight. These percentages were selected to examine the effect of moderate ceramic inclusion on matrix compactness and compressive resistance.

Initially, all dry ingredients including fly ash, fine aggregate, coarse aggregate, and measured alumina powder were thoroughly blended to obtain a homogeneous dry composite. Proper dry mixing was essential to ensure that ceramic particles were evenly distributed throughout the matrix and no localized accumulation occurred. After achieving uniform dry blending, the alkaline activator solution consisting of sodium hydroxide and sodium silicate was added gradually. Continuous hand mixing was then carried out until a workable and cohesive geopolymer ceramic composite mass was obtained.

Thus, three different mixes were prepared for the present study: control geopolymer concrete without ceramic reinforcement, geopolymer concrete containing 7% alumina powder, and geopolymer concrete containing 8% alumina powder. This comparative arrangement enabled the determination of the optimum ceramic replacement percentage.

5.5 Casting of Test Specimens

The freshly prepared geopolymer ceramic composite concrete was poured into standard steel cube moulds of dimensions 150 mm × 150 mm × 150 mm. Prior to casting, all moulds were cleaned properly and their inner surfaces were lubricated to facilitate easy demoulding after setting. The concrete was filled into the moulds in three equal layers.

Each layer was compacted thoroughly using tamping rod strokes to remove entrapped air and to achieve dense particle arrangement. This step was particularly important because the inclusion of fine alumina powder tends to increase internal friction and may otherwise lead to void formation. After complete filling, the top surface of the mould was levelled and finished smoothly so as to maintain a uniform loading area during compression testing.

A sufficient number of specimens were cast for all three mixes to permit testing at different curing intervals. The cast cubes were kept undisturbed for 24 hours for initial hardening.

5.6 Curing of Specimens

After the initial setting period, all cube specimens were carefully demoulded and transferred for curing. Proper curing

was provided for both control and ceramic reinforced specimens so that sufficient geopolymerization reaction and internal bonding could take place. The specimens were cured for two different durations, namely 7 days and 28 days.

During the curing period, the binder matrix gradually

developed dense alumino-silicate gel structure, while the alumina ceramic particles contributed to improved matrix filling and reduced pore spaces. Uniform curing conditions were maintained for all specimens to ensure consistency in strength development and to eliminate any variation caused by moisture differences.

5.7 Compressive Strength Testing

After completion of the curing period, all hardened cube specimens were tested for compressive strength using Universal Testing Machine. Before testing, the cube surfaces were cleaned and checked for dimensional accuracy. Each specimen was centrally placed between the compression platens so that the load could be transferred axially without eccentricity.

The compressive load was applied gradually until visible cracking and complete crushing failure occurred. The maximum failure load corresponding to each specimen was recorded. The compressive strength was then calculated by using the standard formula:

$$f_{cu} = \frac{P}{A}$$

where,

f_{cu} = compressive strength in N/mm²,

P = ultimate failure load in Newton,

A = loaded area of specimen in mm².

For the standard cube specimen of 150 mm × 150 mm, the loaded area was taken as 22500 mm². Average compressive strengths were obtained from all tested cubes for each mix proportion.

5.8 Numerical Analytical Evaluation

The final stage of the methodology involved the numerical analytical comparison of the compressive strengths obtained from the control mix and ceramic reinforced mixes. Average strengths at both 7 days and 28 days were compared to determine the extent of improvement caused by alumina powder inclusion.

The percentage increase in compressive strength was calculated by:

$$\% \text{ Increase} = \frac{f_r - f_c}{f_c} \times 100$$

where,

f_r = compressive strength of reinforced specimen,

f_c = compressive strength of control specimen.

In addition to numerical comparison, the cracking pattern, edge spalling, and crushing mode of each specimen were visually examined during testing. It was analytically expected that alumina powder would act as a rigid ceramic micro-filler, reducing internal voids and improving stress transfer between aggregate and binder. Up to an optimum replacement level, this would lead to enhanced compressive resistance and improved

crack arresting behavior.

Thus, the adopted methodology integrated practical specimen preparation with analytical interpretation to evaluate the structural effectiveness of ceramic matrix reinforced geopolymer concrete under compression loading.

6.RESULTS AND DISCUSSION

6.1 Introduction to Experimental Results

The present chapter discusses the experimental observations and analytical interpretation obtained from the compressive strength investigation of geopolymer concrete reinforced with ceramic alumina powder. Three categories of concrete specimens were considered in the study, namely conventional geopolymer control concrete, geopolymer concrete with 7% alumina powder replacement, and geopolymer concrete with 8% alumina powder replacement. All specimens were tested after curing periods of 7 days and 28 days in order to evaluate both early age and final compressive behavior.

The primary objective of this result analysis was to determine whether the inclusion of ceramic matrix reinforcement contributes positively toward strength enhancement and crack resistance of the geopolymer concrete. Since alumina powder possesses high hardness, dense particle characteristics, and superior compressive bearing ability, it was analytically expected to improve internal packing and reduce void formation within the concrete matrix. The compressive strength values obtained during testing were therefore compared carefully with the control mix to establish the structural effectiveness of ceramic reinforcement.

6.2 Compressive Strength Results of Control and Reinforced Specimens

After completion of the curing period, all concrete cube specimens were tested under Universal Testing Machine and the ultimate failure loads were recorded. Using the standard compressive strength relation,

$$f_{cu} = \frac{P}{A}$$

the compressive strengths were calculated for all specimens.

From the above values, it is clearly observed that the incorporation of alumina powder significantly influenced the compressive performance of geopolymer concrete. Both reinforced mixes exhibited higher compressive strength than the conventional control mix at 7 days as well as at 28 days. However, the maximum improvement was obtained in the specimen containing 7% alumina powder replacement, whereas the 8% replacement specimen showed only moderate gain when compared with the 7% specimen.

The average compressive strength values obtained are presented below.

Sr. No.	Mix Identification	Alumina Powder Replacement	Average Compressive Strength at 7 Days (MPa)	Average Compressive Strength at 28 Days (MPa)
1	Control Mix	0%	29.84	41.26
2	Ceramic Reinforced Mix 1	7%	33.72	46.91
3	Ceramic Reinforced Mix 2	8%	31.95	44.38

This indicates that the inclusion of ceramic particles improved the internal structural compactness of the concrete, but excessive ceramic concentration beyond the optimum limit may have reduced binder continuity and workability, thereby restricting further strength enhancement.

6.3 Comparative Analysis of Strength Improvement

To understand the exact contribution of ceramic matrix reinforcement, the percentage increase in compressive strength over control concrete was calculated by using:

$$\% \text{ Increase} = \frac{f_r - f_c}{f_c} \times 100$$

where,

f_r = compressive strength of reinforced specimen,
 f_c = compressive strength of control specimen.

The analytical comparison is presented below.

At 7 Days Curing:

For 7% Alumina Replacement:

$$\% \text{ Increase} = \frac{33.72 - 29.84}{29.84} \times 100 = 13.00\%$$

For 8% Alumina Replacement:

$$\% \text{ Increase} = \frac{31.95 - 29.84}{29.84} \times 100 = 7.07\%$$

At 28 Days Curing:

For 7% Alumina Replacement:

$$\% \text{ Increase} = \frac{46.91 - 41.26}{41.26} \times 100 = 13.69\%$$

For 8% Alumina Replacement:

$$\% \text{ Increase} = \frac{44.38 - 41.26}{41.26} \times 100 = 7.56\%$$

The above calculations clearly show that 7% alumina powder replacement produced the highest strength enhancement in both curing periods. The percentage increase remained consistently above 13%, which confirms that moderate ceramic reinforcement significantly improves compressive behavior. On the other hand, although 8% replacement still showed improvement over control concrete, the increase was comparatively lower, suggesting that the ceramic dosage had crossed the most effective matrix densification limit.

6.4 Failure Pattern and Structural Behaviour of Specimens

Apart from numerical compressive strength values, important observations were also made regarding the physical failure pattern of the tested cube specimens. During loading, the control concrete specimens exhibited early formation of vertical cracks followed by edge spalling and sudden crushing failure. The crack propagation was comparatively wider, indicating lower resistance to internal stress redistribution.

In contrast, the ceramic reinforced specimens demonstrated delayed crack initiation and relatively more compact crushing behavior. Particularly in the 7% alumina reinforced cubes, the visible cracks appeared at a comparatively higher load and the final failure was less abrupt than the control specimen. This behavior indicates that the alumina particles acted as rigid micro-fillers and crack arresting points within the geopolymer binder matrix. Due to the dense ceramic inclusion, the internal void spaces were reduced and the transfer of compressive stress from binder to aggregate occurred more uniformly.

The 8% alumina reinforced specimens also showed better crack resistance than the control mix; however, slight brittleness and sharper edge fracture were noticed when compared with the 7% mix. This may be attributed to the fact that excessive ceramic particles can create localized stiff zones and reduce the homogeneous continuity of the geopolymer binder. Therefore, although strength remained improved, the failure became comparatively more rigid.

6.5 Discussion on Optimum Ceramic Replacement

Based on the complete analytical comparison and physical behavior of tested specimens, it can be concluded that the addition of ceramic alumina powder had a definite positive influence on the mechanical performance of geopolymer concrete. The ceramic particles improved the density of the binder matrix by filling internal micro-pores, thereby reducing weak zones responsible for premature crack formation. Furthermore, due to the high hardness and compressive bearing nature of alumina, the concrete exhibited better stress carrying capacity under axial loading.

Among the selected replacement levels, 7% alumina powder was

found to be the optimum percentage for the present investigation. This mix provided the highest compressive strength, the greatest percentage improvement over control

concrete, and comparatively stable failure behavior. The 8% replacement mix also performed better than conventional concrete, but the marginal reduction in strength gain indicated that excessive ceramic inclusion can adversely affect workability and binder continuity.

Hence, the results clearly establish that controlled addition of ceramic matrix reinforcement in geopolymer concrete can significantly enhance compressive resistance and structural compactness when used within an optimum dosage range. The present findings validate the suitability of alumina powder as an effective ceramic strengthening constituent for advanced concrete composite applications.

7.CONCLUSION

The present study was conducted to investigate the effect of ceramic matrix reinforcement on the compressive strength and structural behavior of geopolymer concrete through experimental testing and numerical analytical evaluation. In this research, alumina powder was selected as the ceramic reinforcing material because of its high hardness, dense particle structure, superior thermal stability, and excellent resistance to deformation. The main objective was to examine whether the addition of alumina powder as a partial replacement of fly ash binder could improve the strength carrying capacity and crack resistance of geopolymer concrete.

For this investigation, M40 grade geopolymer concrete was prepared as the control mix, and ceramic reinforced concrete specimens were developed by introducing alumina powder at 7% and 8% replacement levels. Standard cube specimens were cast, cured for 7 days and 28 days, and then tested under compressive loading using Universal Testing Machine. The ultimate failure loads were converted into compressive strength values and compared analytically with the control concrete.

From the experimental results, it was clearly observed that the inclusion of alumina powder improved the compressive performance of geopolymer concrete. Both ceramic reinforced mixes showed higher compressive strength than the conventional control mix at both curing ages. This confirms that the ceramic particles contributed positively toward strengthening the internal concrete matrix. The alumina powder acted as a micro-filler and occupied the internal pores and voids present in the geopolymer binder, thereby producing a denser and more compact composite structure. Due to this improved compactness, the transfer of compressive stress became more uniform and the concrete was able to sustain higher load before failure.

Among the selected replacement levels, the specimen containing 7% alumina powder exhibited the best overall performance. It showed the maximum compressive strength and the highest percentage improvement over the control concrete. This indicates that at 7% replacement, the ceramic particles were distributed effectively throughout the matrix and produced better interfacial bonding with the surrounding binder. The 8% alumina reinforced specimen also showed improvement compared to the control mix, but the increase was lower than that of the 7% specimen. This proves that excessive ceramic addition beyond the optimum

level may reduce matrix continuity and slightly affect workability, resulting in comparatively lower strength gain.

During testing, the control concrete specimens displayed earlier crack formation and sudden crushing failure, whereas the ceramic reinforced specimens showed delayed cracking and denser failure patterns. This behavior demonstrates that alumina powder also improved the crack arresting capacity of the concrete and helped in resisting internal stress concentration.

Therefore, based on the complete experimental observations and analytical comparison, it can be concluded that alumina powder is an effective ceramic matrix reinforcement material for improving the compressive strength and structural stability of geopolymer concrete. The optimum replacement percentage for the present investigation was found to be 7%, which provided the best balance between matrix compactness, crack resistance, and ultimate load carrying capacity. Hence, the study confirms that controlled ceramic reinforcement can be successfully used for the development of stronger and more durable high-performance concrete composites for future structural applications.

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