SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V12I5P113

Volume 12 Issue 5, 157-166, May 2025

Original Article

Assessment of Influence of Different Activator Precursors on Strength and Workability of One Part Geopolymer Concrete Mixes Exposed to Marine Environments

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Received: 09 March 2025 Revised: 11 April 2025 Accepted: 10 May 2025 Published: 31 May 2025

***Abstract** - Concrete structures in coastal areas deteriorate rapidly due to harsh environmental conditions. One-Part Geopolymer Concrete (OGPC) offers an environmentally sustainable substitute for traditional concrete, providing superior strength and promising fresh-state properties. Unlike traditional concrete, OGPC consists of dry binders and activators, eliminating the need for Portland cement. The activator precursor is a critical factor in OGPC performance, which influences polymerization and strength development. Therefore, selecting an appropriate activator requires attention. In the present study, the OGPC mixes were prepared using different precursors as activators to determine their influence on fresh and strong properties. The study's key parameters were the chemical composition ratios, types of activators, workability, compressive and splitting tensile strength. The OGPC mixes were evaluated by performing the slump tests, compacting factor test, flow table test to assess the workability in the fresh state, axial compression test, and splitting tensile strength for strength performance in the hardened state. The results showed that using sodium meta silicate and sodium carbonate provides excellent performance for OGPC in all the test conditions. The optimum dosage and chemical proportions of the precursors have also been proposed from the experimental result analysis. The strength properties were compared to the traditional concrete option to ascertain the high-strength performance of the OGPC specimens. The study showed the potential of the utilize of OGPC as a substitute concrete for traditional concrete, with a promising performance in strength and workability being the essential requirements of the structures exposed to the severe exposure conditions in Marine environments.*

***Keywords** - Alkali Activator precursors, Compressive Strength, Marine environment, One-part Geopolymer Concrete, Sustainability.*

1. Introduction

Concrete structures situated in maritime environments are exposed to severe degradation due to exposure to aggressive conditions such as high salinity, sulfate attacks, chloride ingress, and constant wetting and drying cycles. These factors lead to significant durability concerns, including reinforcement corrosion, reduced mechanical strength, and increased permeability, which can severely affect coastal infrastructure's structural integrity and service life [1].

Ordinary Portland Cement (OPC) based conventional concrete is plagued by serious durability issues when applied to marine environments. One of them is vulnerability to corrode embedded steel reinforcement through chloride attack, resulting in cracking, spalling, and weakening of structural strength [2]. Secondly, OPC-type concrete has inadequate resistance to sulphate attack, which has a tendency to cause expansion, disintegration, and weakening of mechanical strength over time. Its relatively high permeability also fosters the infiltration of aggressive ions, with attendant deteriorating impacts [3]. Apart from performance issues, the manufacturing of OPC is resource-intensive and is responsible for a very large share of total global CO_2 emissions, with environmental sustainability being an issue.

In spite of extensive research on alternative cementitious systems, few studies exist on the formulation and performance of One-Part Geopolymer Concrete (OGPC) in marine environments. There are available studies that have focused on two-part geopolymer systems, which, being effective, have practical drawbacks due to mixing and handling difficulties. Due to this, there is a clear gap in research on the impact of various solid activator precursors on the fresh properties and strength characteristics of OGPC in marine exposure conditions. Closing this gap is a necessity to establish sustainable, durable, and effective alternatives to OPC concrete in aggressive environments.

One-Part Geopolymer Concrete (OGPC) has arisen as a viable substitute for traditional concrete, particularly for structures in marine environments. Unlike OPC, OGPC utilizes industry by-products, including fly ash, metakaolin, or GGBFS, which serve as a main binder, activated by solid activators like sodium Meta silicate and sodium carbonate to initiate the geopolymerization process [4, 7]. OGPC exhibits superior resistance to chemical attacks, reduced permeability, and enhanced mechanical properties, making it a viable option for infrastructure exposed to harsh coastal conditions [5]. Moreover, OGPC is a more environmentally friendly alternative because of its smaller carbon footprint and reduced energy consumption compared to Ordinary Portland cement-based concrete.

The role of activator precursors in OGPC is crucial in determining its fresh and hardened properties. Activators play a key role in dissolving aluminosilicate sources and facilitating the polymerization process, which significantly influences the mechanical strength, setting time, and workability of the mix [6, 8]. However, the selection of suitable activators and their optimal proportions remains a challenge. Different activator precursors exhibit varied effects on geopolymerization kinetics, rheology, and long-term durability, making it essential to assess their influence systematically.

Some works have also examined the performance of OGPC under marine exposure. As a consequence, the emergence of a one-part geopolymer has been gaining momentum in recent years. Like traditional OPC-based concrete, OGPC also utilizes a "just add water" formulation, allowing the pre-mix aluminosilicate precursor and solid activator to be combined directly with the water. [9-11], In an early study by Koloušek et al. [10], one-part mixes were produced using the direct calcination of powdered hydroxide and kaolin at 550 °C for 4 hours. Nonetheless, established mixes had an extremely poor compressive strength after 7 days, merely 1 Mpa [11]. Additionally, the calcination treatment to activate albite using sodium hydroxide or sodium carbonate. Their final mix had a compressive strength of approximately 40 MPa at the age of 28 days. Attempts have also been made to formulate a one-part geopolymer using conventional aluminosilicate substances, including fly ash and GGBS. Prepared a one-part geopolymer by blending sodium metasilicate powder or the mixture of solid sodium metasilicate and sodium hydroxide with fly ash or slag [9, 12]. The twenty-eight-day compressive strength values for pure fly ash and slag geopolymer binders were determined to be 9.45 MPa and 50 MPa, respectively. Apparently, pure slag is superior to pure fly ash for growth in strength.

Marine durability is one of the most important performance specifications for structural materials. Studies [17, 19] have indicated that geopolymer concretes, especially GGBFS-blended systems, have improved resistance to chloride ion penetration, sulfate attack, and efflorescence compared to OPC. There is limited literature on OGPC performance in marine environments, especially for the optimization of activator type and amount in the workability-strength balance. Moreover, the synergistic action of ternary binder (e.g., FA–GGBFS–SF) and specially prepared activator mixes in OGPC is still not optimally exploited. The present research attempts to fill this gap by critically investigating the influence of different activator precursors (SS, SC, SH and CH) and dosages on fresh and hardened properties of OGPC mixes subjected to simulated marine environmental conditions.

1.1. Novelty and Significance

The significance of the current work resides in its novel methodology for evaluating the influence of different activator precursors on OGPC performance. This research aims to optimize the chemical proportions and dosage of activators to achieve an ideal equilibrium between workability and strength, ensuring the feasibility of OGPC in marine environments. By providing experimental insights into the effects of sodium Meta silicate and sodium carbonate as activators, this study enhances the comprehension of the geopolymer technology by offering experimental recommendations for the development of durable and sustainable coastal infrastructure.

2. Experimental program

The research investigation sought a full determination of the effect of various activator precursors on the characteristics of both fresh and hardened One-Part Geopolymer Concrete and mortar. The key components of the program consist of material selection, mix design, sample preparation, testing procedures, and data analysis. The methodology was developed in accordance with relevant standards and previous research findings [13].

2.1. Material Selection

The primary materials used in this study include commercial by-products such as Fly Ash (FA) (Sourced from Wanakbori, Gujarat), GGBFS, silica fumes and OPC Cement for control mix as binders. These materials were selected based on their proven reactivity and effectiveness in geopolymerization [14]. The activator precursors investigated include sodium Meta silicate, sodium carbonate, calcium hydroxide and sodium hydroxide in varying proportions. The chemical composition of Sodium Meta Silicate (Na_2SiO_3 $9H_2O$) was 16: 32 by % of the mass of the material for Na_2O and SiO_2, respectively, Sodium carbonate, Calcium Hydroxide with 99.9 wt. % purity and Sodium Hydroxide flakes with 99.9 wt. % purity was crushed to powder form, having a molar ratio of 14:1 for the given water content at the later stage of wet mixing of the constituents. Coarse and fine aggregates were sourced following the standards to ensure consistency in mix design. The general properties of all powder forms, namely fly ash, GGBFS and silica fume, have been tested by doing the XRF investigation done at the sprint testing solution at Mumbai, which is displayed in Table 1.

Table 1. Chemical compositions of binder material

Compositions (% by mass)	OPC	Fly Ash	GGBFS	Silica Fume
SiO_2	19.1	50	36.7	92.8
Al_2O_3	4.9	28	17.2	0.6
Fe_2O_3	2.8	12	1	0.3
CaO	63.5	6.5	34.62	-
MgO	1.3	6	8.9	0.6
SO_3	3.1	-	-	-
MnO	0.2	-	-	-
TiO_2	0.3	0.1	-	-
K_2O	0.5	1.5	-	-
P_2O_5	0.1	-	-	-
Na_2O	0.01	0.2	-	-
LOI	4.5	6	5	4

2.2. Mix Proportions and Preparation

A complete set of ten mixtures, including alkali-activated mortar, was designed from which the control mixture consisted of Ordinary Portland Cement. Mix proportions of various mortars evolved are displayed in Table 2. All mixes of mortar employ a water-to-binder proportion of 0.35 and activator/binder proportions of 0.20 and 0.24; a Fine Aggregate (FA)-to-binder ratio (S/B) equaling 3.0 was utilized for all combinations and subjected to testing for compressive strength. There was no water reducing additive applied to the mortar mixture.

OGPC mix designs were done for M50 grade concrete to get the best concrete design mix that should reach the required workability value, which includes a slump value of 120 mm and a compressive strength at age 28 days of 59 MPa. The mix design procedure in IS 10262:2019 [15] for OPC concrete was applied for OGPC with a change in the binder and water content. OGPC concretes were blended by the traditional method in a 70-L capacity rotating pan mixer.

Table 3. Mix compositions of OGPC mixes are given. In this, mixes no 1 to 4 where W/B of 0.35, Activator/Binder of 0.25, Targeted density of concrete is 2408 kg/m^3 and mixes no 5 to 6 where W/ (B+A) of 0.35, Activators+ Binder equal to 420 kg, Targeted density of concrete is 2434 kg/m^3.

The study focuses on OGPC and aims to establish sustainable alternatives to composites based on Portland cement. However, the two major barriers to commodity are the utilization of substantial amounts of user-unfriendly liquid activators and hot curing. This learning addresses these challenges by emergent normal heat-cured OGPC. Figure 1 Overall methodology for the manufacture of a one-part geopolymer.

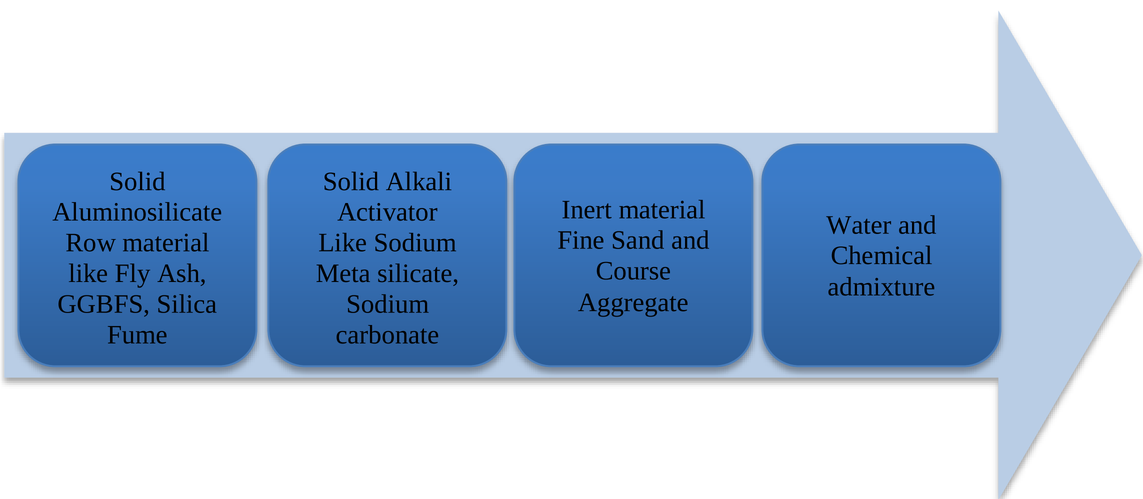

Fig. 1 Overall methodology for the manufacture of a one-part geopolymer

2.3. Casting, Curing and Testing Procedures

A set of 70.6 x 70.6 x 70.6 mm-sized mortar specimens were prepared to assess the compressive strength of mortar by virtue of different activators. Concrete samples in the shape of a set of cubes, as well as cubes, size 0.15 x 0.15 x 0.15m, were prepared to assess OGPC compressive strength. The cast of mortar and concrete specimens led to the OGPC and OPC concrete specimens remaining in the laboratory for twenty-four hours at a room temperature of 27 °C. Following this period, the samples were slowly separated from the mold, and subsequently, the OGPC concrete specimens, as well as the mortar specimens, were cured in normal conditions within the laboratory at 25 ± 2 °C until the actual day of measurement.

The fresh characteristics of OGPC were evaluated using the slump test, flow table test, and compaction factor test.

The tests were used to evaluate the flow ability and cohesiveness of the mixes. Compressive strength tests were performed at 14 days and 28 days as per IS 516 (Part 1/Sec 1): 2021 [16]. Cube specimens (0.15 × 0.15 × 0.15m) were prepared and cured in natural conditions and tested in the Compressive Testing Machine (CTM).

3. Results and Discussion

3.1. Compressive Strength of Mortar Mixes

The compressive strengths of each mixture of OGP and OPC Mortar at 3 and 28 days are represented in Figure 2. It should be observed that the mortal with binder to activator ratio of 0.20 had a relatively lesser strength build-up compared to binder activator ratio of 0.24.

Table 2. The information related to the mixture ratios of the various prepared One Part Geopolymer Mortars

Material	**Binder* %**	**Activator* %**	**Binder**				**Fine Aggregate (Sand)**	**Activator**				**Water Content**
			OPC	Fly Ash	GGBFS	Silica fume		SS	SC	CH	SH	
Mixes			Quantity per Specimen in gm									
M0	OPC-100	_	200	_	_	_	600	_	_	_	_	70
M1	FA-50 GGBFS-50	SS-16 SC-8	_	100	100	_	600	32	16	_	_	70
M2	FA-50 GGBFS-50	SS-16 CH-8	_	100	100	_	600	32	_	16	_	70
M3	FA-50 GGBFS-50	SS-16 SH-8	_	100	100	_	600	32	_	_	16	70
M4	FA-50 GGBFS-50	SS-24	_	100	100	_	600	48	_	_	_	70
M5	FA-50 GGBFS-50	SS-10 SC-10	_	100	100	_	600	20	20	_	_	70
M6	FA-50 GGBFS-50	SS-10 CH-10	_	100	100	_	600	20	_	20	_	70
M7	FA-50 GGBFS-50	SS-10 SH-10	_	100	100	_	600	20	_	_	20	70
M8	FA-50 GGBFS-50	SS-20	_	100	100	_	600	40	_	_	_	70
M9	FA-40 GGBFS-50 SF-10	SS-20	_	80	100	20	600	40	_	_	_	70

Table 3. The formulation of one part geopolymer concrete mixtures

Material	**Binder* %**	**Activator* %**	**Binder**		**Activator**				**FA** (Sand)	**Coarse Aggregate**		**Water Content**
			FA	GGBFS	SS	SC	CH	SH		10 mm	20 mm	
Mixes			Quantity per kg/ m^3									
M1	FA-50 GGBFS-50	SS-16.66 SC-8.34	190	190	63.33	31.67	_	_	700	440	660	133
M2	FA-50 GGBFS-50	SS-16.66 CH-8.34	190	190	63.33	_	31.67	_	700	440	660	133
M3	FA-50 GGBFS-50	SS-16.66 SH-8.34	190	190	63.33	_	_	31.67	700	440	660	133

M4	FA-50 GGBFS-50	SS-25	190	190	95.00	_	_	_	700	440	660	133
M5	FA-40 GGBFS-40	SS-10 SC-10	168	168	42.00	42.00	_	_	718	436	713	147
M6	FA-30 GGBFS-50	SS-20	126	210	84.00	_	_	_	718	436	713	147

***** *GGBFS-Ground Granulated Blast-Furnace Slag, FA-Fly Ash, SS-Sodium Meta silicate, SC-Sodium Carbonate, SH-Sodium Hydroxide, CH-Calcium Hydroxide, SF-Silica Fume, OPC-Ordinary Portland Cement.,*

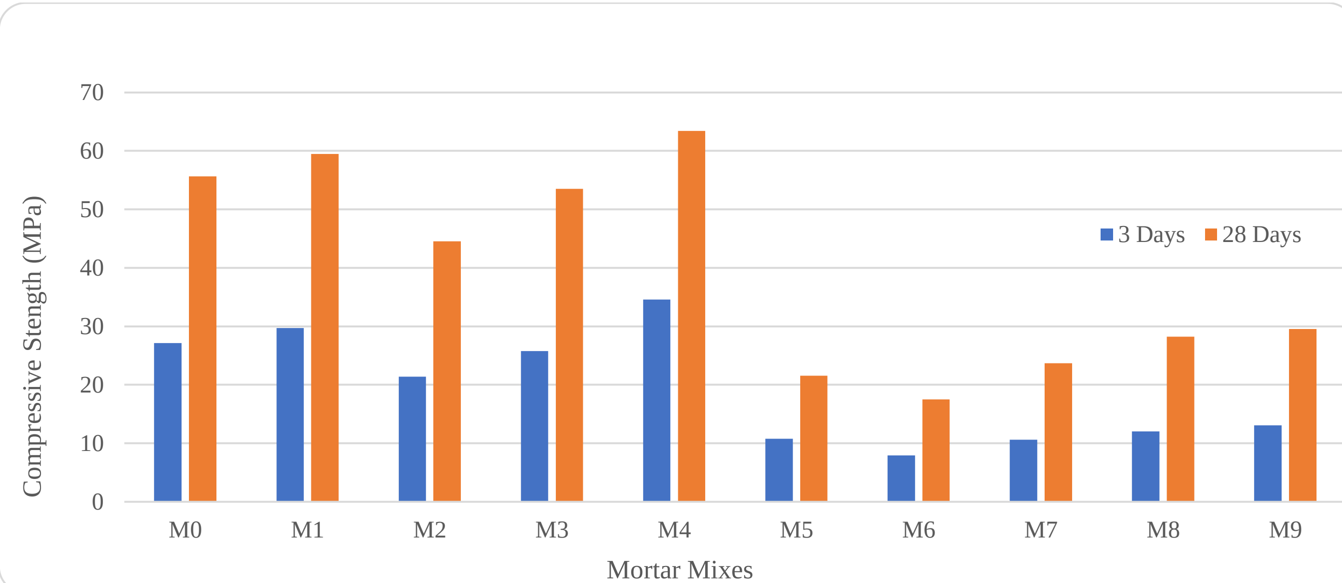

Fig. 2 The compressive strength of several mortar mixes

The sodium Meta silicate containing solid activators were similar otherwise, especially for mixes M1 and M4 [7]. However, both mixes consistently produced higher strengths than each mix of OPGM that used an alkali solution as an activator. Additionally, it has been shown that the mixture of SS with SC has a satisfactory activating effect; however, such is not the case with interactions between sodium Meta silicate and calcium hydroxide and sodium hydroxide. Replacing sodium carbonate with sodium hydroxide and calcium hydroxide as solid activators improved the strength of specimens, as mixes M1 and M5 showed higher strength compared to mixes M2-M3 and M6-M7.

The specimens show an increased sensitivity to the effects of efflorescence, caused by the reaction of alkaline constituents with carbon dioxide, and finally leading to the deposition of white carbonate salts on the specimen surfaces, mainly at higher dosages of Na_2O in the geopolymer matrix. Moreover, sodium Meta silicate alone showed an excellent performance [8] as it reached 63.40 MPa at 28 days while surpassing the strength of M0 by 55.67 MPa.

3.2. Workability Responses

Workability is an essential criterion in evaluating the fresh characteristics of One-Part Geopolymer Concrete (OGPC). It determines the ease of mixing, placing, and finishing required for homogeneous compaction and long-term strength [19]. Workability of OGPC mixes was evaluated by compacting factor test, slump test and flow table test according to Indian standards [18].

3.2.1. Slump Test Results

The slump test results provide valuable insight into the workability of the OGPC mixes, with slump values ranging from 120 mm to 140 mm, displayed in Figure 3**.** The highest slump value **(**140 mm**)** was recorded for M6 (SS-20%)**,** indicating superior workability due to the higher SS content, which enhances the dispersion of binder particulates and reduces internal friction. Similarly, M4 (SS-25%) exhibited a relatively high slump (135 mm), further confirming the positive influence of silicate-rich activators on improving fluidity. On the other hand, M3 (SS-16.66%, SH-8.34%) displayed the lowest slump (120 mm), suggesting that Sodium Hydroxide (SH) reduces workability due to its strong alkali nature, which leads to rapid setting and reduced free water availability. M1 (SS-16.66%, SC-8.34%)**,** M2 (SS-16.66%, CH-8.34%) and M5 (SS-10%, SC-10%) exhibited moderate slump values (125 mm, 130 mm, and 130 mm**,** respectively), indicating that Sodium Carbonate (SC) and Calcium Hydroxide (CH) contribute to moderate workability improvements but are less effective than silicate-based activators. These findings align with previous studies [4, 20], which emphasize that the selection of an activator plays a pivotal role in assessing the fresh-state characteristics of geopolymer concrete. Overall, the results suggest that higher sodium Meta-silicate content enhances workability, while hydroxide-based activators tend to reduce the slump due to increased reactivity and faster setting.

3.2.2. Flow Table Test Results

The results of the flow table test indicate variations in the workability of the OGPC mixes, with flow percentages ranging from 68% to 76%, displayed in Figure 4. The highest flow percentage (76%) was observed in M6 (SS-20%) which also exhibited the highest slump value (140 mm) and compacting factor (0.98), suggesting that increasing the Sodium Meta Silicate (SS) content enhances fluidity and reduces internal resistance.

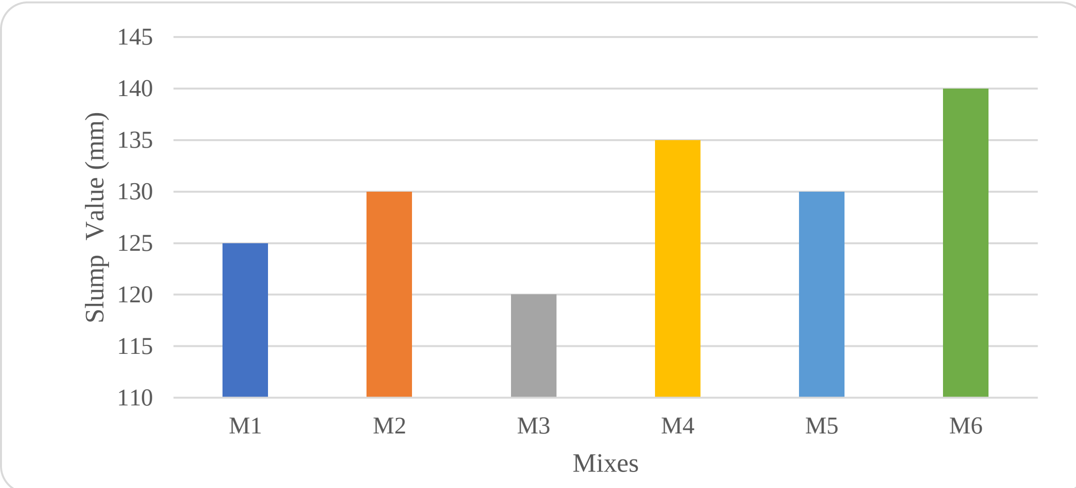

Fig. 3 Slump value of different mixes of OGPC

Similarly, M4 (SS-25%) demonstrated a high flow percentage (74%), reinforcing the role of silicate-based activators in improving workability. On the other hand, M3 (SS-16.66%, SH-8.34%) recorded the lowest flow percentage (68%), indicating reduced flow ability due to the presence of Sodium Hydroxide (SH), which accelerates early-stage stiffening and reduces free water availability. M1 (SS-16.66%, SC-8.34%) and M5 (SS-10%, SC-10%) showed comparable flow percentages role of silicate-based activators in improving workability. On the other hand, M3 (SS-16.66%, SH-8.34%) recorded the lowest flow percentage (68%), indicating reduced flow ability due to the presence of Sodium Hydroxide (SH), which accelerates early-stage stiffening and reduces free water availability. M1 (SS-16.66%, SC-8.34%) and M5 (SS-10%, SC-10%) showed comparable flow percentages (70% and 73%, respectively), signifying that Sodium Carbonate (SC) contributes to moderate workability. Meanwhile, M2 (SS-16.66%, CH-8.34%) exhibited a slightly higher flow percentage (72%), indicating that Calcium Hydroxide (CH) provides better dispersion than hydroxide-based activators but lower than high-silicate content mixes. Overall, the results highlight the significance of the activator type and dosage in influencing th workability of OGPC. Higher silicate content improves flow ability, while hydroxide-based activators reduce it. These findings align with previous research [19,20], emphasizing the critical role of activator selection in achieving an optimal geopolymer concrete mix.

3.2.3. Compacting Factor Test Results

The compacting factor test results ranged from 0.92 to 0.98, as displayed in Figure 5, indicating variations in workability based on the binder and activator compositions. M6 (SS-20%) exhibited the highest compacting factor (0.98), correlating with the highest slump value (140 mm) and flow percentage (76%), suggesting that increased sodium Meta Silicate (SS) content enhances workability by reducing internal friction and improving particle dispersion. Similarly, M4 (SS-25%) recorded a high compacting factor (0.97), further reinforcing the role of silicate-based activators in improving flow ability. In contrast, M3 (SS-16.66%, SH-8.34%) showed the lowest compacting factor (0.92), which is consistent with its lower slump (120 mm) and flow percentage (68%), likely due to the high viscosity and rapid reaction of Sodium Hydroxide (SH), which causes early stiffening. Mixes M1 (SS-16.66%, SC-8.34%) and M2 (SS-16.66%, CH-8.34%) demonstrated moderate compacting factors (0.94 and 0.95, respectively), indicating a balance between cohesion and fluidity, with Sodium Carbonate (SC) and Calcium Hydroxide (CH) improving workability to some extent.

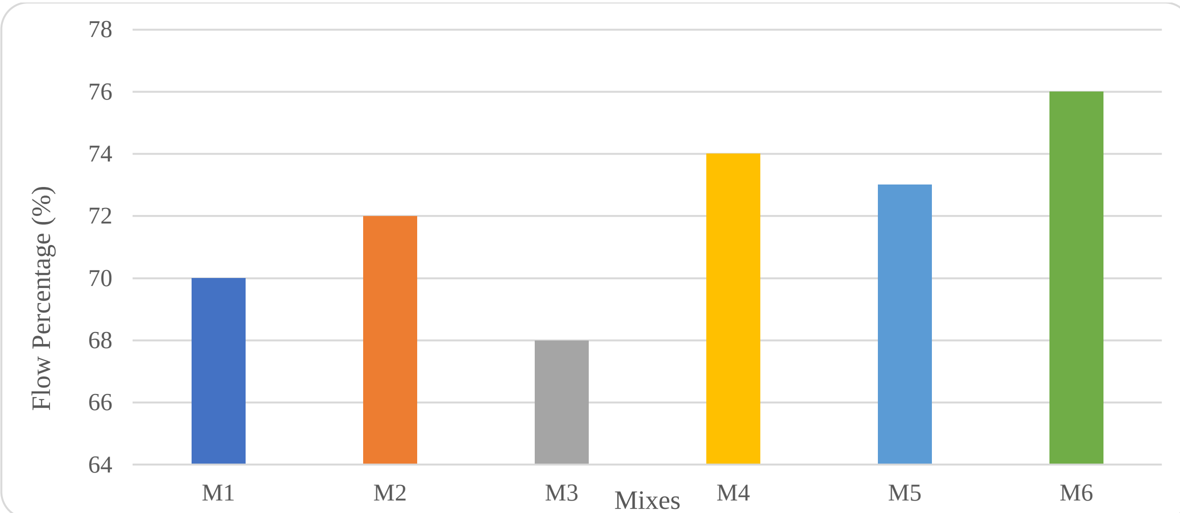

Fig. 4 Flow percentage of different mixes of OGPC

Meanwhile, M5 (SS-10%, SC-10%) had a compacting factor of 0.94, suggesting that reducing sodium silicate content negatively impacts the ease of compaction. Overall, higher silicate content improved workability, while hydroxide-based activators reduced compatibility. These findings corroborate with other studies [4, 20], underscoring the importance of activator selection in achieving an optimal mix for geopolymer concrete applications.

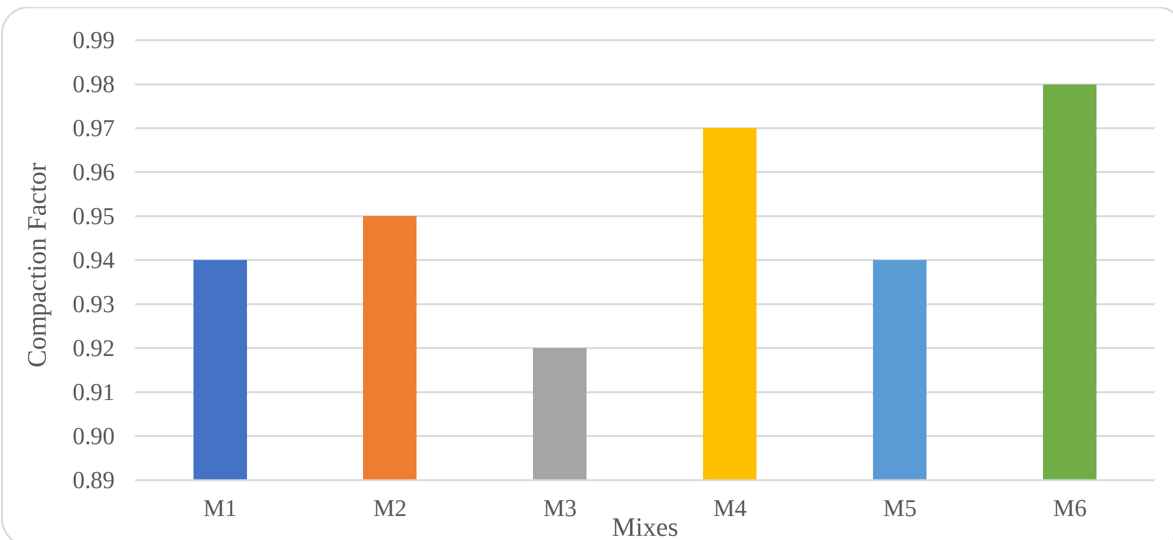

Fig. 5 Compaction factor of different mixes of OGPC

3.2.4. Discussion on Workability Trends

The results of the slump test, compaction factor, and flow percentage indicate that the workability of OGPC is strongly influenced by the choice and amount of activators. The highest slump value (140 mm) and flow percentage (76%) were recorded for M6 (SS-20%), indicating superior workability. This is likely due to the increased silicate content, which enhances lubrication and reduces internal friction among particles [4, 6]. Conversely, M3 (SS-16.66%, SH-8.34%) recorded the lowest slump (120 mm) and flow percentage (68%), suggesting that Sodium Hydroxide (SH) negatively affects workability due to increased viscosity and rapid reaction kinetics, leading to premature setting.

3.3. Compressive Strength of OGPC Mixes

Compressive strength is a fundamental property that defines the load-bearing capacity and durability of One-Part Geopolymer Concrete (OGPC). The compressive strength of OGPC combinations was assessed at 14 and 28 days to analyze the influence of different activator precursors displayed in Figure 6. The results revealed that activator choice significantly impacts strength development, consistent with previous studies [20]. OGPC mixes activated with SS and SC exhibited superior compressive strength compared to sodium Meta silicate alone as well as other combinations of there. The 28-day compressive strength of the mixture based on SS and SS was 70.96 MPa, whereas sodium Meta silicate alone -based mixes achieved 58.34MPa. This finding aligns with research by [9], who reported that sodium Meta silicate enhances geopolymerization reactions, leading to a denser microstructure and improved mechanical performance.

3.4. Significance of Different Precursors on Strength Variation

The compressive strength results obtained from different One-Part Geopolymer Concrete (OGPC) mixes indicate that the selection of precursors significantly influences the strength development of geopolymer matrices. The variations in strength among different mixes can be attributed to the type and ratio of activators, which serve a pivotal function in the polymerization process and the micro-structural densification of geopolymeric binders.

3.4.1. Impact of various Activators on Strength Improvement

The maximum compressive strength at 14 days (54.03 MPa) and 28 days (70.96 MPa) was recorded for M1 (SS-16.66%, SC-8.34%), indicating that a together of Sodium Meta Silicate (SS) and Sodium Carbonate (SC) provides an optimized alkali environment that enhances polymerization. The presence of sodium carbonate is known to improve geopolymerization efficiency by facilitating the dissolution of aluminosilicate phases, leading to a denser microstructure [20, 21].

In contrast, M2 (SS-16.66%, CH-8.34%) and M3 (SS-16.66%, SH-8.34%) showed lower compressive strengths, particularly M3 (41.33 MPa at 28 days), suggesting that Sodium Hydroxide (SH) and Calcium Hydroxide (CH) do not contribute to strength development as effectively as SC. Prior research has indicated that excessive hydroxide content can lead to microcracking due to high reaction heat and alkali saturation, reducing overall strength [12, 19].

M4 (SS-25%) exhibited a compressive strength of 58.34 MPa at 28 days, demonstrating to facilitate an increased SS content enhances geopolymerization, though slightly lower than M1. This confirms findings from earlier studies that suggest an optimal balance of silicate content improves the mechanical characteristics of OGPC [9].

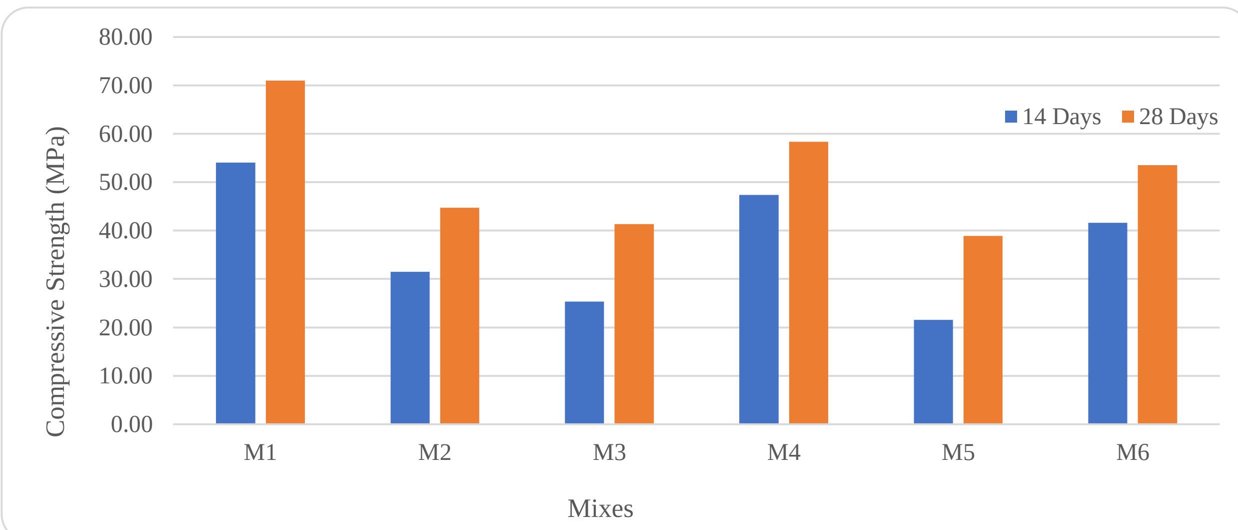

Fig. 6 The compressive strength of various mixtures of OGPC

The lowest strength was observed for M5 (SS-10%, SC-10%), which achieved only 38.90 MPa at 28 days, indicating that a lower SS content limits geopolymerization efficiency. M6 (SS-20%) achieved moderate strength (53.55 MPa at 28 days), suggesting that a Single Activator (SS) at 20% produces a relatively strong geopolymer matrix, though not as effective as the combination of SS and SC seen in M1.

3.5. Optimum Mix Design Composition and Reasons for Performance

Considering workability and strength as key parameters, M1 (SS-16.66%, SC-8.34%) emerges as the optimum mix design for OGPC applications. This mix maintains adequate workability (125 mm slump, 70% flow percentage) while achieving the maximum compressive strength (70.96 MPa at the age of 28 days) due to improved dissolution of aluminosilicate precursors and enhanced polymerization. Similar observations have been made in previous research, where the inclusion of sodium carbonate contributed to better matrix densification and reduced porosity [6]. The combination of SS and SC ensures optimal reaction kinetics, refined pore structure, and a well-densified matrix, rendering it appropriate for high-strength uses in aggressive marine conditions.

These findings support past studies emphasizing the role of sodium meta-silicate and carbonate activators in enhancing geopolymer properties [20, 21]. Thus, M1 is recommended as the most efficient and sustainable alternative to conventional concrete for enhanced durability and performance.

3.6. Application and practical implications

The findings of this study determine that OGPC blends, particularly with sodium silicate (SS) and sodium carbonate (SC) activators, have excellent compressive strength and workability under marine conditions. This suggests suitability for coastal and offshore constructions, where the resistance to sulphate and chloride attack is of the utmost importance. The dry mix and one-part system also have the benefit of logistical simplicity in handling, storage, and site mixing, which makes remote or resource-constrained construction work a possibility. The reduced carbon footprint compared to OPC-based systems also supports the application of OGPC in sustainable construction practices.

3.7. Future Scope and Limitation of Study

This work focused mainly on evaluating the mechanical properties and workability of OGPC mixes under simulated marine exposure conditions, excluding long-term durability tests or in-depth microstructural studies. Statistical analysis of the results was limited to descriptive comparisons. There should be follow-up research that investigates the long-term performance of OGPC mixes in real marine environments, such as resistance to chloride penetration, shrinkage, and corrosion behaviour. Advanced analytical techniques and life-cycle studies should also be employed to further elucidate the environmental and structural performance of OGPC in real applications.

4. Conclusion

The experimental investigation examined the mechanical properties of geopolymer mortar and one-part geopolymer concrete mixes, focusing on compressive strength at various curing ages, workability characteristics, and activator compositions.

- Higher Sodium Meta Silicate (SS) content improves compressive strength, as observed in M4 (SS-24%) and M1 (SS-16%, SC-8%).
- SC-based activators (sodium carbonate) performed better than Calcium Hydroxide (CH) and Sodium Hydroxide (SH) in both mortar and concrete mixes.
- One-part geopolymer concrete, particularly M6, demonstrated good workability without significant strength reduction.
- Fly ash content should be optimized, as reducing FA in M5 and M6 resulted in lower strength development.

Although OGPC is advantageous to a great extent, with the benefits of a lower environmental footprint and resistance to harsh marine conditions, compromises must be made. These are sensitivity to activator composition, strength variations at early- ages, and controlled mixing and curing conditions for reproducible performance. The research has established M1 and M4 as the best mixtures for structural purposes, achieving a suitable compromise between strength and workability. These findings contribute to the emerging literature favouring sustainable substitutes for OPC-based concrete; however, more research is needed to examine durability, cost factors, and practical implementation at a larger scale.

Funding Statement

The research for this study was financially supported by the GUJCOST under the Science, Technology, and Innovation (STI) Scheme, Government of Gujarat, India, by Grant Approval Number GUJCOST/STI/2023-24/341.

Acknowledgments

I sincerely acknowledge the guidance and support of Dr. Ankur C. Bhogayta for their invaluable insights and encouragement throughout this research. I am grateful to Marwadi University, Rajkot, for their provision of the resources and equipment in the laboratory required to conduct this research effectively. Thanks to my research peers and co-authors for the useful feedback and collaboration, which improved the research process. I also extend my appreciation to the faculty members and technical staff for their assistance. Finally, I would like to thank my friends and family for their support and encouragement throughout this journey.

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