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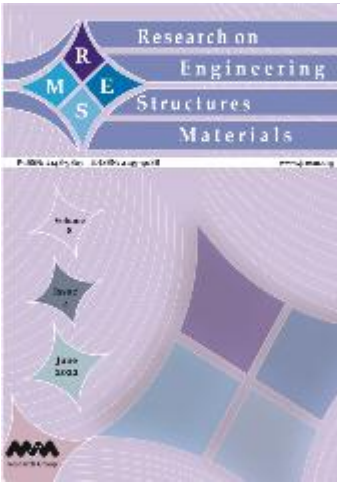

Parametric study on the performance of industrial byproducts based geopolymer concrete blended with rice husk ash & nano silica

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Research Article

Parametric study on the performance of industrial byproducts based geopolymer concrete blended with rice husk ash & nano silica

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Abstract

In this study, Geopolymer concrete (GPC) blended with fly ash (FA), ground granulated blast furnace slag (GGBS), rice husk ash (RHA), and nano-silica (NS) developed and investigated in three aspects: In the first aspect of GPC (FA+GGBS), FA varied from 0-100% of GGBS at 10 % intervals to determine the optimum proportion of FA-GGBS. In the second aspect of GPC (FA+GGBS+RHA), RHA varied from 0-25% of FA at 5% intervals with a constant of 30% GGBS attained from the first aspect of the study. In the third aspect of GPC (FA+GGBS+RHA+NS), NS was replaced with 1, 3, and 5% with the optimum proportions of GGBS (30%) and RHA (15%) obtained from the first and second aspects of the study. The fresh and hardened properties of GPC were obtained at 7 and 28 days under ambient curing. The compressive strength improved while FA was replaced by GGBS (0-100%) from 27.75 to 45 MPa. Meanwhile, workability has decreased to 0.81 from 0.97. Hence, the optimized proportion of FA and GGBS was obtained as 70:30 from the workability aspect. RHA replacement provided compressive strength increment up to 15% (39.5 MPa), but workability gradually decreased (0.92 to 0.84) from 0 to 25%. So, the optimum proportion of RHA was achieved by 15% from the second aspect. In the third aspect, the workability increased from 0.89 to 0.92 while NS replacement (0-3%) with FA. Also, compressive strength has improved from 39.52 to 41.95 MPa. Thus, the optimized NS proportion gained at 3% of NS. Overall, this study provides a view of industrial by-product utilization as part of GPC in optimal proportions.

1. Introduction

The building sector is growing rapidly due to urbanization [1]. Therefore, globally the need for cement production has also risen with infrastructure development [2]. Generally, cement-based concrete is widely used in the building industry [3, 4]. Moreover, the cement industry releases carbon dioxide (CO_2) of 0.85 - 1 ton during the manufacturing processes of one-ton cement which is part of global warming. Furthermore, it estimates that airborne CO_2 emissions are between 5-7% [5–8]. Much recent research has shown interest in finding a substitute material to replace cement [9] with Geopolymer Concrete (GPC), which uses pozzolanic materials and alkali activators [10]. GPC is an environmentally safe alternative to traditional cement-based concrete and contributes to reduce CO_2 emissions. The emissions from geopolymer binders' production are significantly lower compared to cement, possibly around 0.1 to 0.3 tons of CO_2 per ton [11, 12]. Joseph Davidovits invented

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Geopolymer (GP) in 1978 as an alternative to cement [13]. GP is an inorganic aluminosilicate polymer group produced by reacting aluminosilicate materials and a higher amount of silicon and aluminum with the alkaline activator solution (AAS) [14].

Generally, Fly ash (FA) and Ground Granulated Blast Furnace Slag (GGBS) are the industrial and steel plant by-products as main precursors used in GPC [15]. AAS is a mixture of Sodium Silicate (Na_2SiO_3) or Potassium Silicate (K_2SiO_3) and Sodium Hydroxide (NaOH) or Potassium Hydroxide (KOH) [16]. However, sodium-based solutions are more economical than potassium-based solutions [17]. FA is pulverized fuel ash from exhaust gases of coal-based thermal power plants by-product that improves the rheology and alkali-aggregate reaction of artificial pozzolan due to the high amorphous silica content [18]. Overall, FA generation of 300-600 MT in 2020, occupied up to 3235 km^2 of land for disposal, and India produced 271 MT of FA from 200 power plants during 2021-2022 [19]. GGBS is a solid waste discharged in high quantities by the iron and steel industry. The global GGBS production was 377 MT in 2021. The benefits of GGBS on concrete improves the strength, decreases the voids, and reduces the permeability. Also, it can generate heat during the hydration process and reduce water demand from the alkali-silica reaction [20–22].

Rice husk (RH) is a by-product of rice mill from paddy. It is usually obtained from rice husk burning and contains silica ash after being removed from cellulose and lignin. 35 MT of RHA has been produced annually from 140 MT of RH obtained from 700 MT of rice production [23]. Rice husk is burnt to 300-700 degrees Celsius and made into ashes [24]. Rice Husk Ash (RHA) is a fine active silica material with numerous merits, including strength enhancement, durability, and cost-effectiveness. RHA utilization in concrete is the best solution for waste disposal and reduce carbon dioxide emissions. It gives better strength due to high amorphous silica content, high surface area, and porous structure [25–28]. Generally, FA blends with similar high-silica sources materials like GGBS, Silica fume, RHA, and Nano silica to form a suitable chemical composition of geopolymers [29]. GP has the potential to develop environment-friendly materials by using by-products that are harmful to the environment [30].

1.1. Nano Material

In recent years, Nano materials usage in construction has significantly enhanced the performance of the materials. Nowadays, one of the nanomaterials called Nano Silica (NS) is used in concrete technology, as nano-sized particles act as nano additives [31]. It improves the cementitious matrix, hydration, mechanical properties, and concrete microstructure due to its high specific area. It can improve the density binder matrix that decreases porosity and self-healing ability [32]. Also, it is a cost-effective and eco-friendly material that reduces CO_2 emissions. It was found that a small dosage of NS improved the early age and 28-day strength gain of GP concrete through the attributed effect, pozzolanic reaction [33] its pore-filling properties and reactive pozzolans [34]. It accelerates the polymerization rate and facilitates the development of C-S-H and N-A-S-H in natural pozzolan-based GPC [35]. Since NS particles possess a large surface area, the polymerization process is accelerated [36]. Silica or silicon dioxide nanoparticles increases the mechanical properties [37–39]. GPC is resistant to inflammable and chemical problems [40]. It has low creep and less shrinkage and achieves quick setting time and improved the strength [41].

1.2. Review on Literatures

Globally, extensive researchers have been conducted in the field of GPC to find alternate materials to cement and other precursors. For instance, FA (75%) and GGBS (25%) at various concentrations of NaOH from 8 to 16 M with Na_2SiO_3 to NaOH ratio from 0.5 to 3.0 were analyzed for the optimum molarity and obtained as 14 M with Na_2SiO_3/NaOH ratio as 2.5 in GPC [42]. In addition, GPC made with FA, GGBS, alccofine (0-15%), naphthalene-based superplasticizers (1.5%) were cast to determine the strength. The results proved that GPC attained more strength at 40% FA, 50% GGBS, and 10% alccofine than OPC [43]. Moreover, FA was replaced with RHA to enhance the performance of GPC [44, 45]. However, only 10% of RHA can be replaced with GGBS to gain maximum strength [46]. Overall, it was found that RHA incorporation in GPC can act as additional cementitious material with pozzolanic reaction, binder formation, strength enhancement, and reduces the environmental impact.

On the other hand, the addition of RHA (1.2%) and NS (1%) with FA has improved the strength in GPC which reveals incorporation of NS increases the reactivity and workability of concrete. Hence, NS improve the strength and durability of the GPC [47]. Another study attempted to determine the workability and strength properties of GPC blended with Waste Glass Powder (WGP), FA, GGBS, and MK. The experimental result revealed that GPC with GGBS (55%), WGP (35%), and MK (10%) attained 12% of strength increment [48]. Furthermore, GGBS was replaced with red mud (0-30%) in KOH and K_2SiO_3 as AAS solution to analyze applicability of alternate materials in GPC. The increase in the red mud proportion with GGBS reduced the workability and enhanced the strength up to 12% [49].

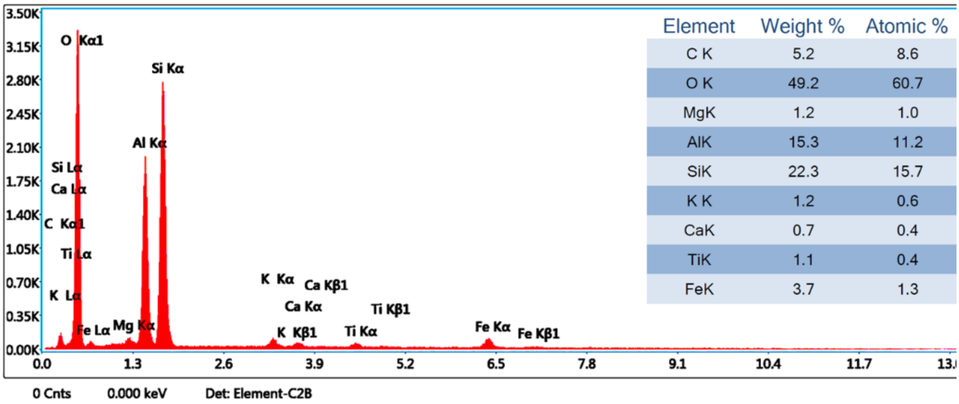
Recently, the strength properties of GPC with RHA, FA, GGBS, and nano TiO_2 (NT) were studied and obtained the maximum strength of 16 % increase with RHA (10%) and TiO_2 (4%) incorporated GPC specimens [50]. Although, 20% of RHA addition produced maximum strength with MK (20%), FA (30%), and GGBS (30%), but further addition of the RHA reduced GPC strength [27]. GPC developed from FA, nano-clay (NC), and NT enhanced strength at 1% of NC and 1.25% of NT. Furthermore, it increased the density of GPC and reduced the pores [51]. Also, another study investigated the modified GPC with NS (0-2.5%) and Silica fume (SF) (0-2.5%) with FA (70%) and GGBS (30%) and obtained as 1.5% as the optimum of both NS and SF [50–52]. NS, micro silica, and alkali-activated slag-based GPC were examined and the addition of 3% NS improved the strength and reduced beyond this limit [53].

Overall, GPC with FA, GGBS, MK, SF, RHA, alccofine, red mud, on various combinations of these materials are investigated to gain the optimum strength FA, a primary GPC binder, has growing demand, so it needs to find an alternative. NS is cementitious material and have superior qualities such as improvement of mechanical properties, durability, workability, and shrinkage reduction. It also enhances bond strength and helps mitigate alkali-silica reaction. These significances make nano silica a valuable additive for improving the performance of GPC structures. This study explores the development of GPC using industrial by-products like FA, GGBS, RHA and NS and to arrive the optimum proportions for workability and strength from different combinations of industrial by products.

2. Materials and Methods

2.1. Fly Ash (FA)

FA is a thermal power plant by-product and can act as primary source material. The FA was obtained from Tuticorin thermal power plant for the study. Class F FA is considered as per ASTM C618 [54] with light grey in color, and has a specific gravity of 2.30. Scanning Electron Microscope (ZEISS EVO18 CARL, Germany) equipped with Energy Dispersive X-Ray Spectroscope (EDX) is non-destructive method and used to analyses the quantitative elemental composition of FA, GGBS, RHA, NS at 1500 magnification, 20 kV acceleration voltage and resolution of 129 (eV). EDX spectrum shows the elemental composition of FA shown in Fig. 1.



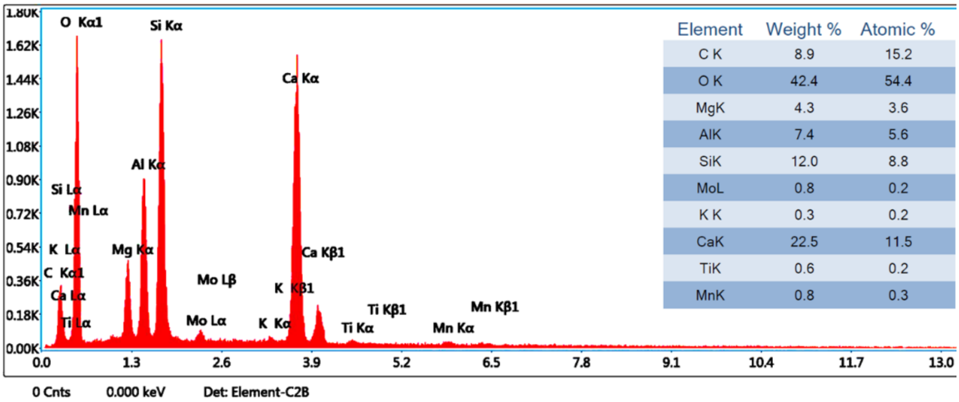
Element	Weight %	Atomic %
C K	5.2	8.6
O K	49.2	60.7
MgK	1.2	1.0
AlK	15.3	11.2
SiK	22.3	15.7
K K	1.2	0.6
CaK	0.7	0.4
TiK	1.1	0.4
FeK	3.7	1.3

Fig. 1 Elemental compositions of FA from EDX Spectrum

The active silica (SiK-22.3%) and alumina (AlK-15.3%) were found utmost quantity compared to other elements in Class F Fly ash (FA) from EDX spectrum. Where k factor (K electrons, closest to the nucleus, are n=1 electrons) represents the net-count ratios of characteristic or intensity X-rays of sample measurement divided by standard of known or reference sample.

2.2. Ground Granulated Blast Furnace Slag (GGBS)

GGBS is a secondary source material obtained from iron industry byproducts. It was obtained from JSW steels for the study. It is white in color with specific gravity of 2.90 and the chemical compositions of GGBS are shown in Fig. 2.



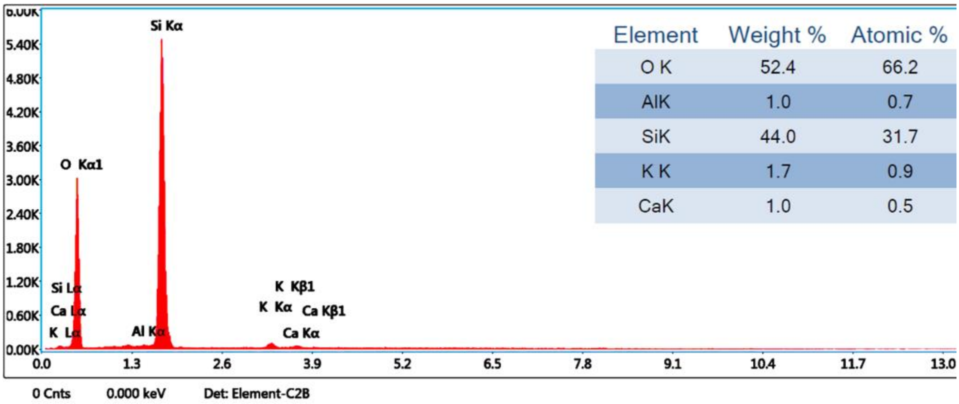
Element	Weight %	Atomic %
C K	8.9	15.2
O K	42.4	54.4
MgK	4.3	3.6
AlK	7.4	5.6
SiK	12.0	8.8
MoL	0.8	0.2
K K	0.3	0.2
CaK	22.5	11.5
TiK	0.6	0.2
MnK	0.8	0.3

Fig. 2 Elemental compositions of GGBS from EDX Spectrum

The EDAX spectrum of GGBS appears calcium (CaK-22.5%), active silica (SiK-12%), alumina (AlK-7.4%) and magnesium (MgK-4.3%) are presented maximum amount compared to other elements in Class F Fly ash.

2.3. Rice Husk Ash

RHA is an agriculture by-product from rice mills. It is generated by flaming the RH under a specific temperature. It is obtained from a local rice mill plant for the study. It is dark grey color and has a specific gravity of 2.18. The elemental compositions of RHA from EDX spectrum are shown in Fig. 3.



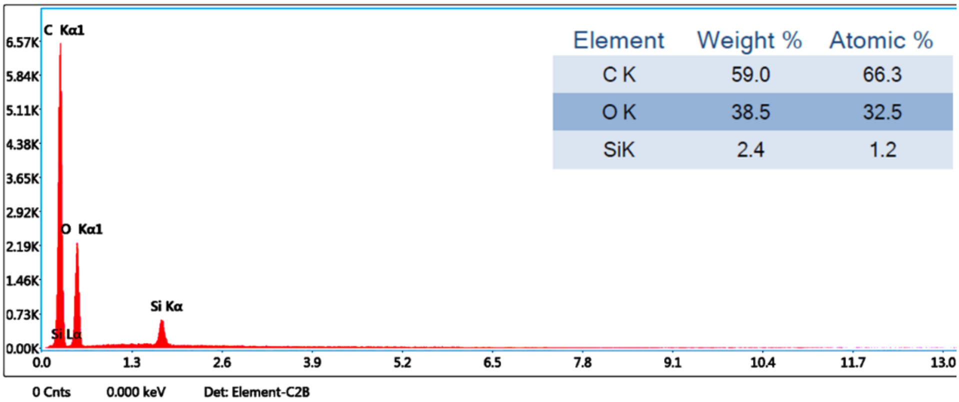
Element	Weight %	Atomic %
O K	52.4	66.2
AlK	1.0	0.7
SiK	44.0	31.7
K K	1.7	0.9
CaK	1.0	0.5

Fig. 3 Elemental compositions of the RHA from EDX Spectrum

From Fig. 3, active silica (SiK-44%) is presented maximum amount compared to other elements in RHA. Oxides are presented due to atmospheric oxygen and potassium and calcium are available in minimum amount which represented in Fig. 3.

2.4. Nano Silica (NS)

NS is in powdered form and purchased from Astra Chemicals, Chennai. It helps in the formation of aluminosilicate gel and contains more silica content in it.



Element	Weight %	Atomic %
C K	59.0	66.3
O K	38.5	32.5
SiK	2.4	1.2

Fig. 4 Elemental compositions of the NS from EDX Spectrum

It is white in color with a specific gravity of 2.4 and elemental composition of NS shown in Fig. 4. The presence of active carbon (CK-59%), oxygen (38.5%) and active silica (SiK-2.4%) was shown in Nano Silica (NS) from spectrum. EDX spectrum proved that pure nano silica was taken for this study. Excess EDX spectrum peak of carbon was presented due to that carbon tape was used to conduct the analysis and oxides due to atmospheric oxygen. Hence, the after deduction of carbon and oxides, the 100% of silica content is available in the sample from Fig. 4.

2.5. Aggregates and Alkaline Liquids

In this study, locally available CA and M sand with the grade of fine aggregate confirmed to Zone-II as per IS383 (2016) [55] and the specific gravity as 2.62 CA of 20 mm size with a specific gravity of 2.91 and density of 1750 kg/m^3 was used. Na_2SiO_3 and NaOH mixture can act as AAS. The specific gravity of NaOH and Na_2SiO_3 were 1.47 and 1.60, respectively.

The workability and the compressive strength of GPC can be enhanced with, the 13 Molarity concentration of NaOH solution [56].

2.6. Experimental Procedure

The NaOH and Na_2SiO_3 solution were used as alkaline liquids. Na_2SiO_3 and NaOH ratio was taken as 1:2.5 and the A/B ratio is fixed as 0.55 [57, 58]. 13M was prepared by dissolving 377 grams of NaOH pellets in a liter of distilled water [59]. The NaOH solution has been mixed 24 hours before casting the specimen. The sodium silicate is mixed with NaOH solution before casting.

Table.1 Mix proportions of GPC with various binder combinations

MIX ID	FA %	GGBS %	RHA %	NS %	FA (kg/m³)	GGBS (kg/m³)	RHA (kg/m³)	NS (kg/m³)
Optimization of binder ratio (FA and GGBS)								
GPG0	100	0	0	0	550	0	0	0
GPG10	90	10	0	0	495	55	0	0
GPG20	80	20	0	0	440	110	0	0
GPG30	70	30	0	0	385	165	0	0
GPG40	60	40	0	0	330	220	0	0
GPG50	50	50	0	0	275	275	0	0
GPG60	40	60	0	0	220	330	0	0
GPG70	30	70	0	0	165	385	0	0
GPG80	20	80	0	0	110	440	0	0
GPG90	10	90	0	0	55	495	0	0
GPG100	0	100	0	0	0	550	0	0
Optimization of RHA								
GPR0	70	30	0	0	385	165	0	0
GPR5	65	30	5	0	357.5	165	27.5	0
GPR10	60	30	10	0	330	165	55	0
GPR15	55	30	15	0	302.5	165	82.5	0
GPR20	50	30	20	0	275	165	110	0
GPR25	45	30	25	0	247.5	165	137.5	0
Optimization of Nano Silica								
GPN0	55	30	15	0	302.5	165	82.5	0
GPN1	54	30	15	1	297	165	82.5	5.5
GPN3	52	30	15	3	286	165	82.5	16.5
GPN5	50	30	15	5	275	165	82.5	27.5

The precursors such as FA, GGBS, RHA, and NS under various combinations were mixed with alkaline liquids along with the aggregates. After mixing, the concrete mixture was transferred into 150×150×150 mm cubes, 150×300 mm cylinder moulds, and 100×100×500 mm prism. Triple specimens were cast for every GPC mix proportions and the cube, cylinder and prism specimens were removed from the moulds and cured at ambient temperature after 24 hours of casting.

Fig. 5 Specimens preparation and test setup of compression (cube), split tensile (cylinder) and flexural (prism)

The cube specimens have undergone compression test as per ASTM C63 [60] and split tensile strength tests have been carried out on the cylinder specimen as per ASTM C496 [61]. A concrete prism is used to analyze flexural strength as per IS 516-1959 at 7 and 28 days [62]. The preparation and testing of specimens shown in Fig. 5

3. Results and Discussions

3.1. Workability and Strength

Workability is obtained for freshly mixed GPC that is to be placed and compacted for the uniform flow of mix in the concrete without segregation. The GPC workability is determined from the standard compaction factor test as per IS 1199-1959 [61]. The workability of FA-GGBS with 0-100% proportions range from 0.97 to 0.81 of compaction factor value shown in Fig. 6. The workability is reduced with the increase in GGBS proportions.

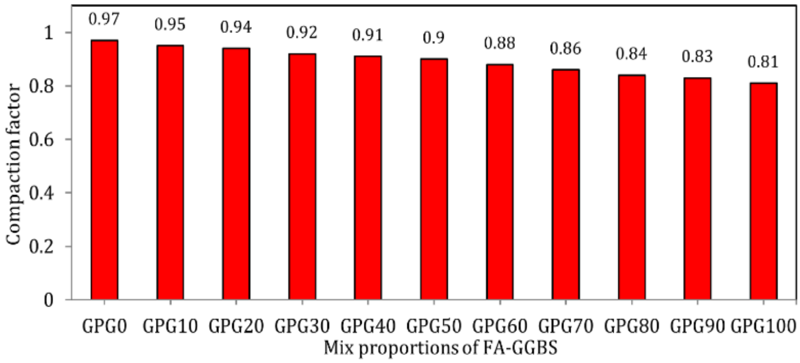


Fig. 6 Compaction factor value for proportions of FA and GGBS

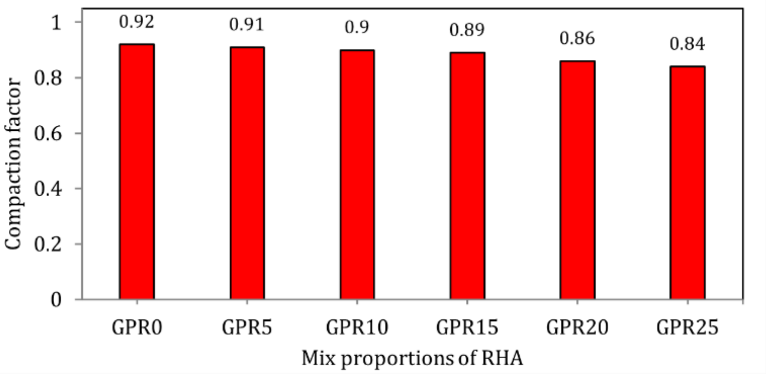


Fig. 7 Compaction factor value for proportions of FA, GGBS, and RHA

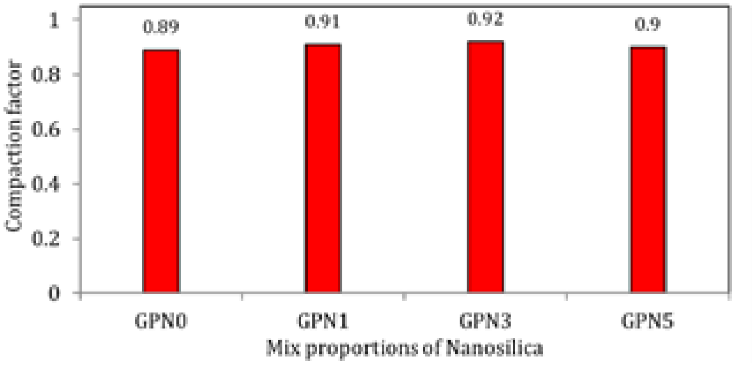


Fig. 8 Compaction factor value for proportions of FA, GGBS, RHA, and NS

According to IS 456-2000, compaction factor 0.85 to 0.92 were considered the medium degree of workability. Hence, the optimum workability is fixed as 0.92, which is medium degree workability obtained at GPC30 from Fig. 6. The workability of GPC based RHA with 0-25% proportions was performed by compaction factor experiment, and the results range from 0.92 to 0.84 shown in Fig. 7. The workability declined in higher RHA proportions. Based on the strength factor, the optimum degree of workability is obtained as 0.89. GPC workability improved from 0.89 to 0.92 at 3% of NS, and it declined to 0.90 at 5% shown in Fig. 8. Hence the optimum workability of NS mixed GPC is obtained at 0.92, which is a medium degree of workability at 3% of NS.

3.1.1 Optimization of FA-GGBS Proportion

The FA-GGBS based GPC was optimized based on the mechanical properties such as compressive strength (CS), split tensile strength (STS) and flexural strength (FS) test. The Mix ID GPG0 to GPG100 was analyzed for the CS, STS and FS test. CS of FA-GGBS proportion at 7-days and 28-days ranges from 13.60 to 29.75 MPa and 27.75 to 45 MPa from Fig. 9. GPC strength increased when GGBS content increased with FA, but workability decreased with the increase of GGBS. STS at 7-days and 28-days ranges from 0.95 to 3.4 MPa and 1.95 to 5.1 MPa from Fig.10. GPC strength increased when GGBS content increased with FA, but workability decreased with the increase of GGBS. So, GPG30 was fixed as the optimum FA-GGBS proportion which is 2.8 MPa at 28 days. FS ranges at 7-days and 28-days from 3.15 to 4.95 MPa and 3.95 to 6.50 MPa indicated in Fig. 11. GPC strength increased when GGBS content increased with FA, but workability decreased with the increase of GGBS. So, GPG30 was fixed as the optimum FA-GGBS proportion at workability factor which is 4.85 MPa at 28 days. Overall, the optimum CS, STS, and FS were obtained from GPG30 at 28 days.

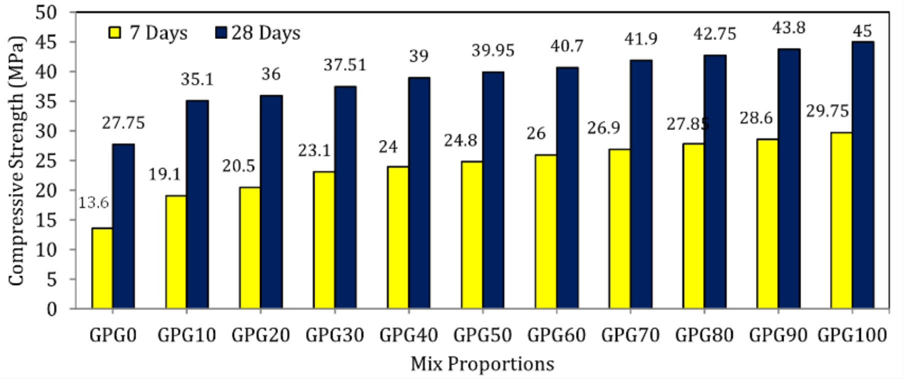


Fig. 9 Compressive strength test for proportions of FA and GGBS

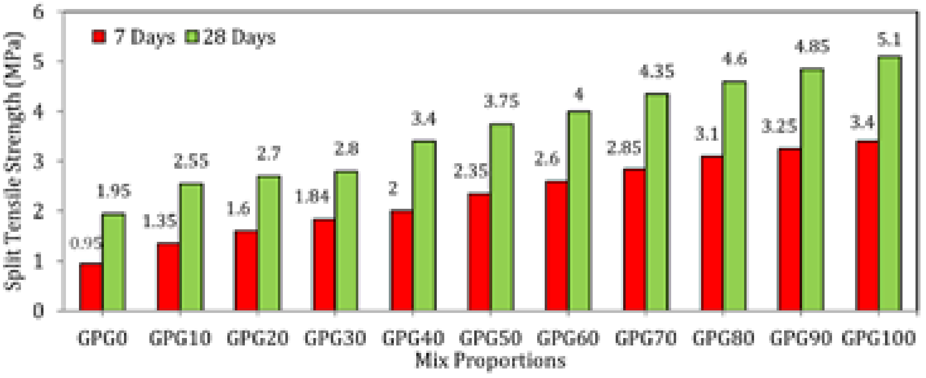


Fig. 10 Split tensile strength test for proportions of FA and GGBS

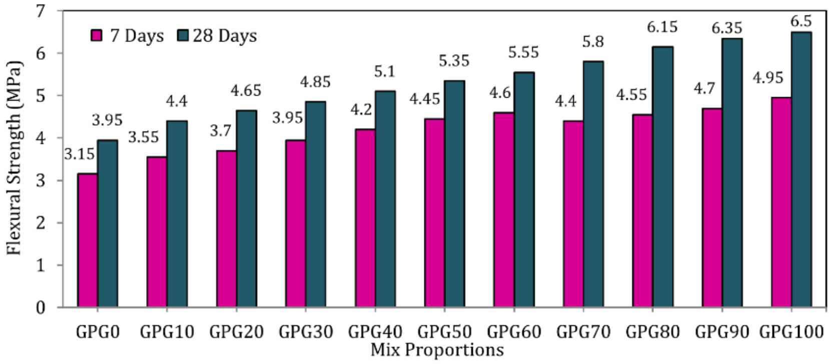


Fig. 11 Flexural strength test for proportions of FA and GGBS

3.1.2 Optimization of RHA proportion

The RHA was optimized with FA and GGBS (30%) based on the value of CS, STS and FS. The optimized proportion of FA-GGBS is taken with constant GGBS proportion and the FA is varied with RHA from 0 to 25% at an interval of 5%. CS of GPC with RHA proportion increases up to 15%, after that the strength decreased. CS of RHA proportions 0 to 15% at

7-days and 28-days ranges from 23.1 to 25.15 MPa and 37.51 to 39.5 MPa and 20% were 22.8 and 37.9 MPa, and for 25% were 21.1 and 36.2 MPa indicated from Fig.12. So, GPR15 was fixed as the optimum RHA-FA-GGBS proportion based on strength concern which is 39.5 MPa at 28 days.

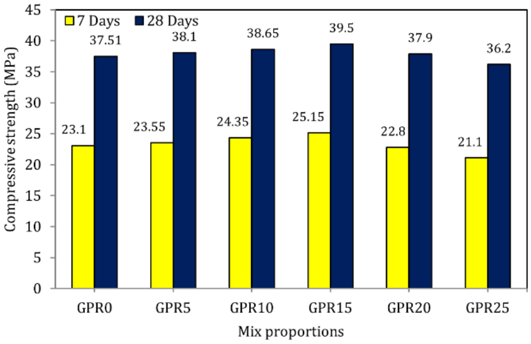


Fig. 12 Compressive strength tests for proportions of FA, GGBS, and RHA

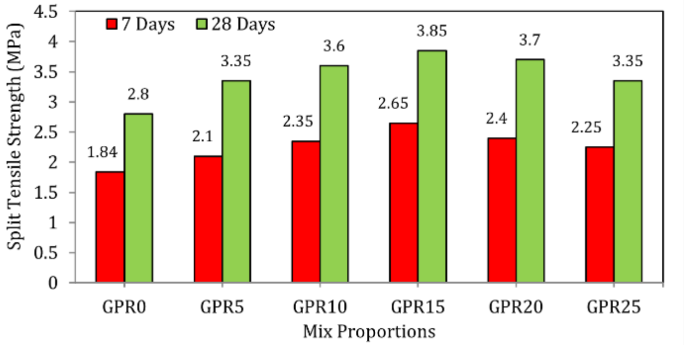


Fig. 13 Split tensile strength tests for proportions of FA, GGBS, and RHA

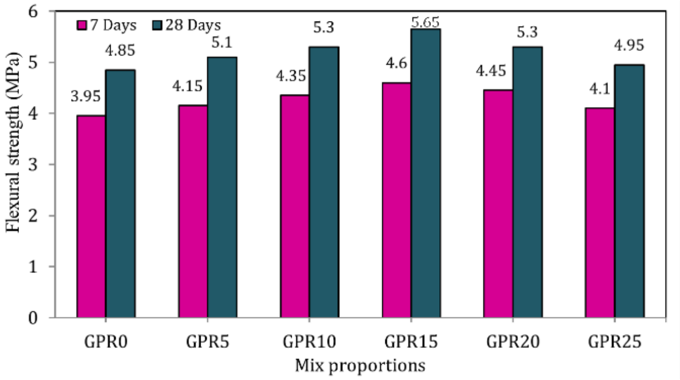


Fig. 14 Flexural strength tests for proportions of FA, GGBS, and RHA

STS of GPC with RHA proportion increases up to 15%, after which the strength decreased. CS of RHA proportions 0 to 15% at 7-days and 28-days ranges from 1.84 to 2.65 MPa and 2.8 to 3.85 MPa and 20% were 2.4 and 3.7 MPa, and for 25% were 2.25 and 3.35 MPa indicated from Fig.13. So, GPR15 was fixed as the optimum RHA-FA-GGBS proportion for strength concern which is 3.85 MPa at 28 days. FS of GPC with RHA proportion increases up to 15% after strength decreases beyond 15%. CS of RHA proportions 0 to 15% at 7-days and 28-days ranges from 3.95 to 4.6 MPa and 4.85 to 5.65 MPa and 20% were 4.45 and 5.3 MPa, and for 25% were 4.1 and 4.95 MPa indicated from Fig.14. Based on the strength concern, GPR15 was fixed as the optimum RHA-FA-GGBS proportion was obtained as 5.65 MPa at 28 days.

3.1.3 Optimization of NS Proportion

Optimization of NS was determined for FA, GGBS (30%) and RHA (15%). The GGBS and RHA proportions were kept constant, and the FA varied with NS from 0 to 5% at an interval of 0, 1, 3, and 5%. CS, STS, FS test results were plotted for GPN0 to GPN5 in Fig. 15-17.

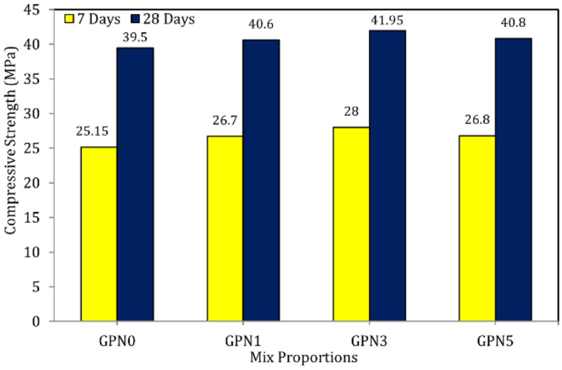


Fig. 15 Compressive strength tests for proportions of FA, GGBS, RHA, and NS

CS increased with NS proportion increased up to 3%, and the strength reduced beyond 3%. CS of NS proportions 0 to 3% at 7-days and 28-days ranges from 25.15 to 28 MPa and 39.5 to 41.95 MPa, whereas for 5% is 26.8 MPa and 40.8 MPa. STS increased with NS proportion increased up to 3%, and the strength reduced beyond 3%. STS of NS proportions 0 to 3% at 7-days and 28-days ranges from 2.65 to 3.4 MPa and 3.85 to 4.25 MPa, whereas for 5% is 3.15 MPa and 4.2 MPa. FS increased with NS proportion increased up to 3%, and the strength reduced beyond 3%. FS of NS proportions 0 to 3% at 7-days and 28-days ranges from 4.6 to 4.95 MPa and 5.65 to 6.1 MPa, whereas for 5% is 4.7 MPa and 5.75 MPa.

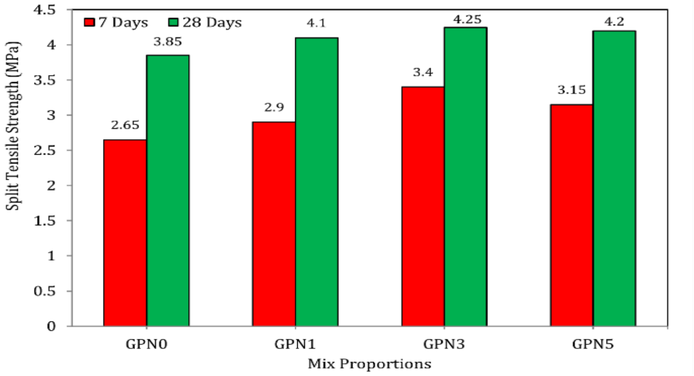


Fig. 16 Split tensile strength tests for proportions of FA, GGBS, RHA, and NS

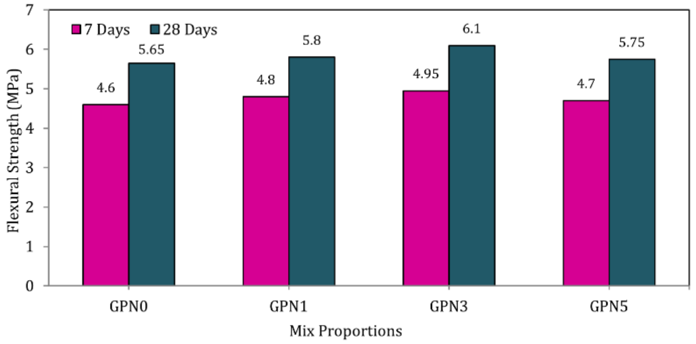
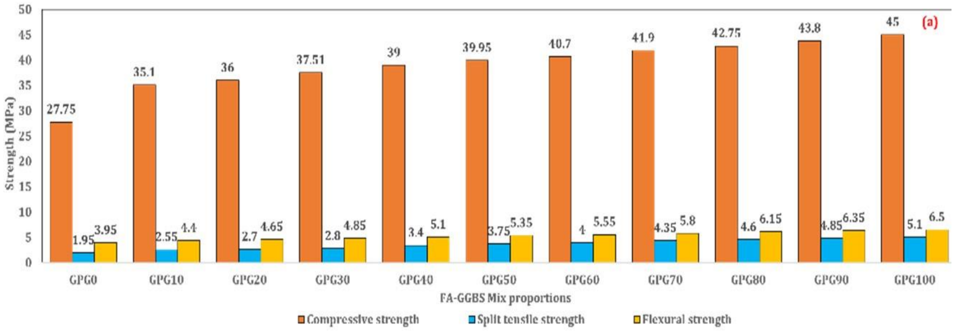


Fig. 17 Flexural strength tests for proportions of FA, GGBS, RHA, and NS

3.1.4 Combined and Optimum Strength of GPC

The combined CS, STS and FS of GPC with FA-GGBS shown in Fig. 18 (a-c). From Fig. 19, the GPC30 provides the test results of CS, STS, FS as 37.51, 2.8, 4.85 MPa, respectively. Also, the workability taken in to the account to obtained the optimum proportion as GPC30. The CS, STS, FS of GPC with different RHA proportion shown in Fig. 19. As the result of strength decrement beyond 15%, the optimum RHA proportion taken as GPR15 can deliver 39.5, 3.85, 5.65 MPa of CS, STS, FS, respectively. Fig. 19 shows the NS optimum proportions fixed as GPN3 (CS-41.95 MPa, STS-4.25 MPa, FS-6.1MPa) due to strength decreased after 3% of NS replacement.

The addition of GGBS influences the strength of GPC due to the higher calcium content than FA and aluminosilicate ratio, which improves the pozzolanic reaction. At the same time, Higher calcium content decreases the workability by reducing setting time in the GPC mix [63, 64]. Also, RHA addition provides supplementary cementitious material and increases the strength of GPC due to its high silica content and pozzolanic properties. However, it reduced more than 15% of RHA addition, causing a reduction of the aluminosilicate ratio in the GPR20 and GPR25. Simultaneously, RHA addition can decrease the workability of the GPC mix due to its finer particle size and higher surface area, which can absorb more water [65, 66]. Moreover, NS addition produces better strength than other GPC mixes due to its highly reactive pozzolanic material. Initially, workability increased up to 3% because the extremely finer particles of NS act as lubricants between particles, thus reducing friction and improving flowability. Simultaneously, it declined after 3% of NS addition due to a high surface area that adsorbs more water [67, 68].



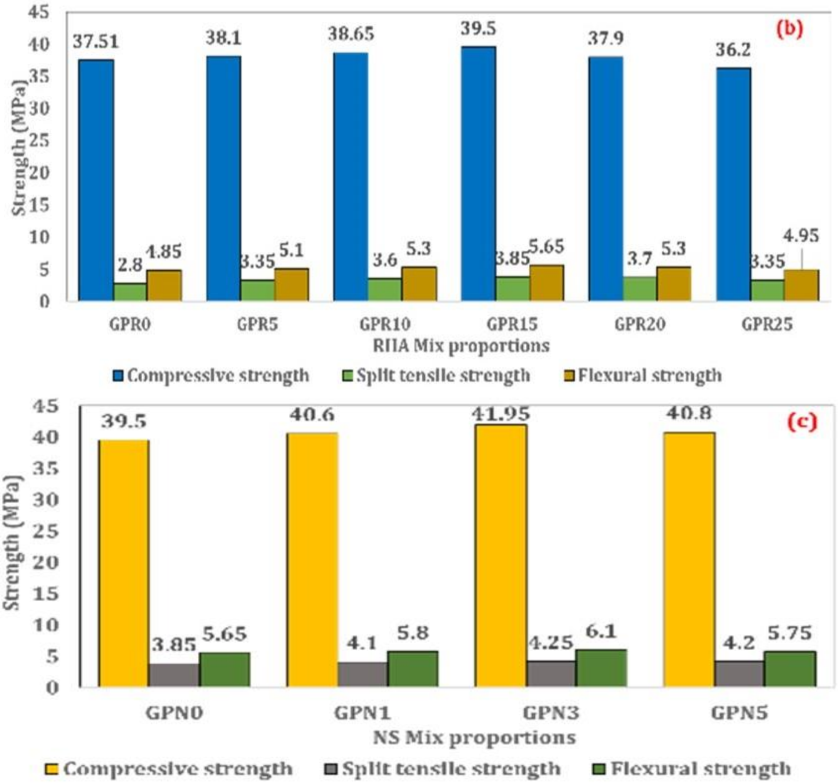


Fig. 18 Combined strength of GPC

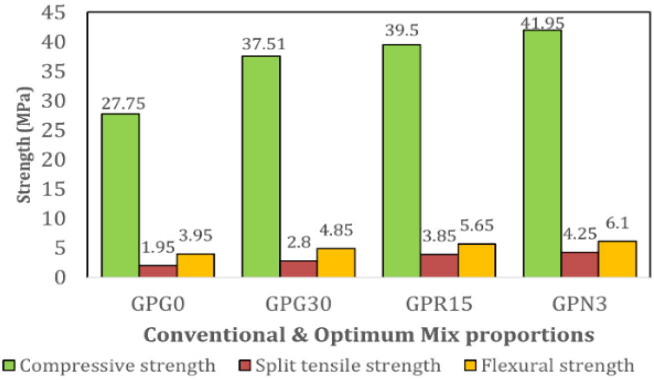


Fig. 19 Optimum strength of GPC

4. Conclusions and Future Research Directions

GPC is an environmentally safe concrete that reduces CO_2 emissions from cement production by replacing cement with industrial waste including FA and GGBS. There has been limited research on the effect of RHA and NS on GPC. Therefore, this study investigated the workability and strength characteristics of GPC incorporated with FA, GGBS, RHA, and NS. The following conclusions were drawn according to results obtained from GPC specimens.

- In the first aspect, with the increase in GGBS content the strength increased, and at the same time, the workability decreased in GPC specimens. Hence, the optimum proportion of 30% GGBS and 70% FA gave the optimum workability and strength at GPG30 mix. Considering all this, strength of GPC is influenced by GGBS in the initial fresh stage.
- In the second aspect, the addition of 15% RHA, 30% GGBS, and 55% FA obtained maximum strength and decreased the strength beyond 15% of RHA. The optimized RHA of 15% RHA gave the optimum workability and strength at GPR15 mix. Hence, GPC strength has increased significantly due to silica in RHA improved the polymer bonds.
- In the third group, 3% of NS, 15% of RHA, 30% of GGBS, and 52% of FA provide optimum strength and better workability at GPN3 due to the pore-filling effect, and the strength decreased beyond 3% as NS fills unreacted areas of GGBS and increased the of GPC strength.

Overall, the study results encourage the use of industrial by-products such as FA, GGBS, RHA, and NS in GPC to reduce the environmental damage from traditional cement production and CO_2 emission. This research recommends to utilizes the FA-GGBS-based GPC to achieve target mean strength. However, to promote sustainability with desired mean strength, this study would suggest replacing up to a certain percentage of RHA with FA. Moreover, to obtain strength with workability, the combination of NS with RHA, GGBS, and FA provides greater development than other combinations. Hence, GPC is a promising sustainable engineering composite material and could be used effectively for building materials.

Also, this paper suggests as future directions for the current study may be the synthesis of RHA-based sodium silicate for GPC and the resistance and volume expansion test on GPC that lay a strong foundation for the research and development in the field of Geopolymer concrete. The high energy required for the manufacturing process of Na_2SiO_3 is high and emits CO_2 from its production. So, Na_2SiO_3 may be substituted by synthesized sodium silicate solution from RHA and NS. Generally, Na_2SiO_3 was produced from the fusion of pure silica sand and sodium carbonate in furnaces at a melting temperature of 1400° Celsius. It emits anthropogenic gases such as CO_2, NO_x, SO_x, and dust that decrease the sustainability of GPC production. However, RHA-based Na_2SiO_3 has been substituted for commercial Na_2SiO_3 due to the equivalent weight ratio of SiO_2/Na_2O, and the process of RHA-based Na_2SiO_3 was comparatively simple and processes such as chemical synthesization by reflux or hydrothermal from RHA and NaOH mixture under minimum temperature from 80° to 140° Celsius. Therefore, the silica-rich RHA-based Na_2SiO_3 is enhancing sustainability by controlling harmful gas emissions during synthesization.

4.1. Assumptions and Limitations of the Study

- The influence of FA, RHA, GGBS, and NS in GPC has not been studied from microstructural analysis such as XRD, FTIR, SEM and EDX. Fresh and mechanical properties test results are assumed to be the effect and impact of materials that are used in GPC.
- The specimens were cured under ambient curing, and the temperature fluctuation might not affect the strength parameters.

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