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Mechanical and durability characterization study on partial replacement of coconut shell in geopolymer concrete

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ABSTRACT

Geopolymer concrete is produced with use of byproduct are the environmentally friendly and positive impact for workable growth. This research, by products such as fly ash and ground granulated blast furnace slag (GGBS) were utilized as binding material in geopolymer concrete. The main aim of the present study is to replace the coarse aggregate by coconut shell and evaluate the mechanical and durability properties of the concrete by varying the 10%, 20%, 30%, 40% and 50%. The study results indicates that, 40% use of coconut shell shows the high strength behaviour than other variations. In order to evaluate the durability properties, water absorption, rate of absorption, acid resistance and sulphate resistance tests was performed. The study results represented that, fly ash and GGBS shows the strong binding cementitious material while using coconut shell as coarse aggregate. the formation of calcium aluminium silicate hydrate(C-A-S-H) gel and siloxane bonds with coconut shell reduce the acid attack and water absorption capacity of the geopolymer concrete.

Keywords: Geopolymer concrete; Coconut shell; Mechanical and durability properties.

1. INTRODUCTION

The beginning of human invention, concrete has possessed huge importance in their life-style. Concrete is a vital building material utilized in various infrastructures projects around the world. In fast developing infrastructures and construction field, demand of basic constituent of concrete such as cement, aggregates and water resources will increasing day by day [1, 2]. Geopolymer is an inorganic material obtained from the result of chemical rection between alkalis and aluminosilicate in waste products. In general, geopolymer were used for medical applications, high fire resistance coating, high temperature ceramics and new binders for fire resistant fiber composites, and as cementing material in concrete. In recent decades, to improve the physical and mechanical behaviour of concrete by mixing of various types of aggregates, binder and other chemical substances. In other hand, cement is a basic element in manufacturing of concrete and it has an extensive negative impact on natural resources. During the manufacturing of cement, huge amount of carbon dioxides (CO_2) released into the environment. In each ton of cement manufacturing emits, almost one ton of CO_2 into environment and consumes nearly 1.6 tons of natural resources [3].

The utilization of geopolymer concrete as an option in contrast to the regular Portland cement concrete has been found to bring about up to 80% decrease in characterized carbon relying upon the sign and activator utilized. A few other life cycle evaluations of geopolymers have demonstrated that geopolymers are feasible other options and more huge improvement in the maintainability can be accomplished with the utilization of constituents and locally accessible materials. The materials utilized in geopolymer concrete are generally byproducts from different modern and rural cycles [4–6]. Geopolymer concrete can be considered all the more harmless to the ecosystem and a compelling method for overseeing huge volumes of wastes produced by different active industries. The utilization of locally accessible materials, for example, laterite soil as fine agrregate can be utilized to work on the supportability of geopolymers. In this manner, the use of geopolymers as a reasonable option in contrast to Portland cement composites would bring about a critical decrease in ozone harming substance release, unrefined substance utilization and compelling waste management [7]. The geopolymer cover is an inorganic polymer gotten from the polycondensation response of aluminosilicates with salts. The geopolymers have nebulous/semi-translucent 3-layered aluminosilicate system structures made by the going with $(SiO_4)^{-4}$ and $(AlO_4)^{-5}$ tetrahedral. As of late, geopolymers have gotten huge fascination in the

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investigation and development industry because of the remarkable exhibition as far as physical and mechanical properties [8].

To reduce the manufacturing of cement and emission rate of CO_2, recent researchers were carried out to identify the substitute material for cement and aggregate in concrete are agricultural waste, industrial waste, various replacement of aggregate. However, to reduce the negative impact of construction industry on environmental ecosystem, researchers are exploring the use of waste generated from industries and agricultural field in construction materials [9, 10]. Predominantly, waste materials from the agricultural field are more efficient and cost effective to make high durable and strengthen concrete in recent days. Consequently, recent decades many researchers were carried out the detailed investigation on various recycled materials replaced for conventional fine and coarse aggregate [11–13]. Coconut shells are a farming byproduct that is generally delivered in tropical countries [14–16].

SHAHRABADI *et al.* [17] analysed the effects of limestone on silcia fume and fly ash based concrete and revealed that, 10% replacement of limestone in silcia fume based concrete gives the good stregnth and less environmental impacts. FORSAT *et al.* [18] investigated the effects of larestan pipeline water and mechanical behaviour of concrete using granite aggregate and the study found that, graphene oxide powder distribution and geometric imperfectness are highly influenced the mechanical properties of the concrete. MIRJAVADI *et al.* [19] assessed the post bearing of reinforced concnrete plates with geometrical imperfection and study found that, 50% replacement of granite aggregate with covnentional aggregate gives good strength properties and improves the mechanical behaviour of the concrete. By consolidating coconut shells as a partial replacement for coarse aggregate in concrete, however it similarly advances feasible practices in construction industry [20, 21].

The recent researcher [22] carried out the detailed evaluation of the optimal mix design with coconut shell ash as a partial replacement for cement in concrete and used various mix proportion such as 10%, 15%, 20% and 25%. They carried out the burning, grinding and sieving process for the preparation of coconut shell for replacement of cement and tested the properties of coconut shell using SEM, EDS, XRF, and DIA analyses. The study found that, 20% replacement of coconut shell in conventional concrete would be the better result in view of structural behaviour and environmental impact. HASAN *et al.* [23] investigated the characteristic of lightweight and green concrete using coconut shell as replacement of conventional aggregate. The various proportion were used to assess the characteristic of green concrete such as 10%, 20%, 30%, 40%, and 50% by weight. The physical and mechanical behaviour of concrete were assessed to find the optimal replacement of coconut shell for conventional concrete. The study found that, 50% replacement of coconut shell shows high strength and less environmental impacts compared with other replacement percentages. LIU *et al.* [1] assessed the engineering properties and economic advantages of recycled aggregate concrete. The study used waste clay bricks and coconut shell for partial replacement of coarse aggregates in conventional concrete. The study assessed the workability, mechanical, thermal conductivity, and other mechanical behaviour of concrete and additionally evaluated the economic advantages of controlled concrete. The study found that, recycled and light weight concrete are satisfied the requirement of conventional concrete. AZIZ *et al.* [2] evaluated the mechanical properties, structural performance of coconut shell lightweight concrete and followed the study followed the 50% replacement of coconut shell reduce the compressive strength around 9% and 18% reduction in drying shrinkage.

Based on the detailed literature studies, coarse aggregate replacement by coconut shell is well studied but the detailed research is required to understand the mechanical behaviour of controlled concrete with partial replacement of coconut shell, fly ash and GGBS [24–26]. The mechanical behaviour of the geoploymer concrete has been improved with increase in percentage of GGBS upto 40% with replacement of cement and fine aggregate. We identified that, fully replacement of cement by fly ash and GGBS with coconut shell studies were are not discussed so far [27–29]. The present study aimed to develop the geopolymer concrete using partial replacement of coconut shell as coarse aggregate, to study the mechanical behaviour of concrete and to assess the durability of controlled concrete with different exposure conditions. The finding of the present study results will more helpful to carry out the further research on partial and fully replacement of coarse aggregate by coconut shell and to understand the strength and durability properties of the coconut shell in concrete.

2. MATERIALS AND METHODS

In general, geopolymer concrete is a part of inorganic polymer material that do not use cement as a binding material for production conventional concrete [30]. The present study used the fly ash (FA) as a primary binding material, GGBS as another cementitious material, natural and M sand used as fine aggregate and natural crushed stones and coconut shell as coarse aggregate. The sodium silicate and sodium hydroxide were used as alkaline solution.

2.1. Fly ash

The present study used calcium-based fly ash (F type), which were byproduct of the thermal power plant currently operate in the northern part of the Tamil Nadu, India. The chemical constituents of the FA were presented in the Table 1. A high percentage of 54.56% of silica dioxide, 28.25% of alumina trioxide, 8.01% of ferrous trioxide, 5.32% of calcium oxide and with other constitution materials.

2.2. GGBS

The GGBS collected from the iron manufacturing company and its properties are 37.25% of silica dioxide, 33.65% of calcium oxide, 13.25% of aluminium dioxide with other constitution materials (Table 1). The specific gravity of the GGBS is 2.8 [31].

2.3. Aggregate

The collected and dried natural river sand was used a fine aggregate. The sieve test was carried out to confirmed the gradation of FA is zone III as per recommend standards. The specific gravity of the FA is 2.65. The novelty of the present study is to replace the conventional coarse aggregate by coconut shell. The properties of the both coarse aggregates were listed in the Table 2. For conventional concrete, the properties of coarse aggregate are 12 mm in size, specific gravity of 2.84 with bulk density of 1620 kg/mm^3. To attain the higher strength with good workability, size of coconut shell is 10 mm, specific gravity is 1.15 and bulk density is 720 kg/mm^3.

2.4. Alkaline solution

The alkaline activator plays a vital role in geopolymer concrete and act as the super plasticizers [32, 33]. Based on the literature studies, sodium hydroxide (NaOH) and sodium silicate ($NaSiO_3$) were chosen as the alkaline activator in present study. The chemical compositions of sodium silicate are Na_2O is 14.7% and SiO_2 is 29.45 and H_2O is 55.9%. The sodium hydroxide pellets with 98% of purity were used to prepare the NaOH solution. The concertation of the NaOH solution is 10M. The alkaline activator was prepared 24h before casting the geopolymer concrete.

3. EXPERIMENTAL TECHNIQUES

3.1. Preparation of samples

The present study aimed to assess the mechanical and durability behaviour of partial replacement of coconut shell aggregate. Consequently, both conventional and coconut replacement concrete were prepared to understand the strength variation [34, 35]. The fly ash, GGBS, fine and coarse aggregate were well mixed for 2 to 3 mins in concrete mixer. The prepared alkaline activator solution was added to the dry mix and additionally water about

Table 1: Chemical composition of fly ash and GGBS.

MATERIAL	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_4	Na_2O	K_2O	LoI
Fly ash	5.32	54.56	28.25	8.01	1.35	0.28	0.56	0.29	0.41
GGBS	33.65	37.25	13.25	0.28	5.98	0.42	1.32	0.78	0.27

Table 2: Conventional and coconut shell aggregate properties.

PROPERTIES	CONVENTIONAL COARSE AGGREGATE	COCONUT SHELL AGGREGATE
Maximum size (mm)	12	10
Specific gravity	2.84	1.15
Bulk density (kg/mm^3)	1620	720
Abrasion test (%)	1.95	1.63
Water absorption (%)	10.12	18.01
Fineness modulus	4.25	3.89

5% weight of fly ash were added to increase the workability of the concrete. The workability of the geopolymer concrete were measured based on the Indian standard recommendations. The fresh concrete was filled in cubes, cylinder and prisms by three layers and each layer were vibrated using tamping rod and finally vibrated each specimen in vibration machine for 30s.

3.2. Mechanical behavior of concrete

To assess the mechanical behaviour of geopolymer concrete, compressive, split tensile and flexural strength test was performed. For compressive strength test, 100 mm cubes were prepared based on the IS 516-1959 and tested at 7, 14, 28, 56 and 90 days. To estimate the flexural strength, prism of size 100 × 100 × 500 mm was prepared and tested based on ATM C78–84 [36]. The cylinders were prepared to estimate the splitting tensile strength of the concrete followed by ATM C 496.

3.3. RCPT

The RCPT was performed to evaluate the rate of chloride penetration in concrete. Due to environmental changes, sea water intrusion and excess amount of chloride groundwater are easily penetrated into the concrete and degrade the strength of concrete [37–39]. The RCPT is the significant test to measure the chloride ion penetration into the concrete specimen in the laboratory scale. The experimental setups are followed by ASTM C 1202-1997 standards. The unit of RCPT is coulomb, the current passed between the specimen and measure in ampere. Already casted and well ambient cured cylinder with a size of 100 mm diameter × 300 mm height is sliced into 100 mm diameter × 50 mm height was taken into experiment. The experiment consists of two different chemical reservoir such as one is 3% of NaCl solution and another one is 0.3N of NaOH solution. The sliced concrete specimen was placed between the two reservoirs and DC current are supplied at the rate of 60 volts for 6 hours. The current passing was measuring every 30 minutes. The experiment setup of RCPT is shown in figure.

3.4. Sulphate resistance test

The sulphate resistance test is one of the important tests to understand the behaviour of concrete toward sulphate attack, more significant in coastal region [40]. In this test, 5% of sodium sulphate powder were mixed in the curing tank and ambient cured geopolymer specimens were taken out and immersed in the solution for 28, 56 and 90 days. The tank was closed with plastic sheet to avoid the evaporation and free from dust in the tank. Every 28 days, new solution was added to maintain the concentration of sodium sulphate in the curing tank and stirred once in a week to avoid the salt settlement on the specimen [15]. After carried out the weight difference, we can understand the amount of sulphate intrusion in each specimen. The variation of compressive strength and weight loss has been calculated at the end of the experiment.

3.5. Acid resistance test

In present study, 5% concentrated sulphuric acid solution added with separate curing tank and immerse the specimen. To keep a constant pH value of water, sulphuric acid solution was added after14 days. For each concrete mix, 3 specimens were used and total of 18 specimens were immersed in the curing tank asper standards recommended by ASTM C 642. The cubes were immersed in the 5% sulphuric acid solution tank with a depth of 30 – 50 cm. The casted geopolymer concrete cubes were cured in ambient environment for 28 days. After curing, both conventional and geopolymer cubes were taken out from the tank and weight was recorded as W1. Three sample cubes were taken out after 28-, 56- and 90-days interval to estimate the variation of compressive strength and weight of the specimen. The final weight was measured and taken as W2. The mass variation was calculate using following formula:

$$\%\ of\ weight\ loss = \frac{W1\ (initial\ weight) - W2\ (final\ weight)}{W1\ (initial\ weight)} \times 100$$

3.6. Water absorption test

The casted specimens were immersed into water for 24 hours and after that, the surface was wiped with clothes and placed into oven at the temperature of 105 ± 5°C. The weight of the specimen before and after placing into oven was measured as Ws (saturated weight) and Wd (dry weight). The water absorption percentage was measure using following equation:

$$water\ absorption = \frac{W_s - W_d}{W_d} \times 100$$

3.7. Rate of absorption

The absorption rate is an important factor to characteristic the behaviour concrete and to understand the homogenous nature of the material used. The rate of absorption test was carried with use of normal water, set of specimens were immersed in it. The experimental setup and arrangement were followed by ASTM C1585-13. The dried samples are cooled at normal room temperature for more than 12 hours [41]. In order to make the impermeable surface, methyl ethyl ketone peroxide was used as non-absorbent solution and applied on the both sides of the specimens. The plastic tubes were used to arrange the bottom of the specimen were clearly touch with the water in the tank. The rate of absorption was estimate using following equation:

$$I = \sqrt{S_t}$$

Where, S is the rate of absorption, t is the time taken, and I is the absorption. The absorption was measured using:

$$I = \frac{\Delta w}{Ad}$$

Δw is the change is the weight before and after immersed to the tank.

4. RESULTS AND DISCUSSION

4.1. Mechanical behaviour of concrete

The mechanical behaviour of concrete such as compressive, split tensile and flexural strength are calculated and listed in Table 3 The study result shows that, target mean strength of conventional concrete is achieved after 28 days and various percentage of coconut shell replacement are showing the higher strength in 40% replacement with coarse aggregate mix compared with conventional mix. About 35.15%, 31.44% and 16.67% of the compressive, split tensile and flexural strength has increased in GC40 mix. Based on the previous studies, coconut shell gradually increased the mechanical properties of the concrete with respect to age of the concrete (Table 3). The result indicates that, fineness nature of fly ash and GGBS gives the major strength, during hydration process coconut shell gives a higher strength and silica content in the fly ash reacts further and gives more bonding to with coconut shell.

4.2. Acid resistance test

In present study, weight loss and compressive strength after 28 days, 56 days and 90 days immersed in the acid has been estimated and shown in Figure 1 and Figure 2. In Figure 1 shows that, weight loss has been increased with increase in number of days immersed in the acid. The conventional concrete mix shows the very low level of weight loss compared with geopolymer concrete mixes. The maximum amount of around 3.5% of weight loss has been recorded in conventional mix. In other mix variation shows that, increasing percentage of coconut shell increases the weight loss in acid resistance test. The results indicates that, coconut shell make the concrete low permeable in acid attack. The penetration of sodium ions and other element is low in all mix. The geopolymer concrete with optimal percentage of coconut shell shows that, strong acid resistance and low permeable concrete.

Table 3: Mechanical behaviour of coconut shell based geopolymer concrete.

S.NO	MIX ID	% OF COARSE AGGREGATE REPLACEMENT	COMPRESSIVE STRENGTH	SPLIT TENSILE STRENGTH	FLEXURAL STRENGTH
			MPa		
1	GC0	0	30.52	2.56	4.05
2	GC10	10	33.26	2.85	4.18
3	GC20	20	36.85	2.96	4.36
4	GC30	30	39.53	3.09	4.52
5	GC40	40	41.25	3.18	4.86
6	GC50	50	38.59	3.02	4.42

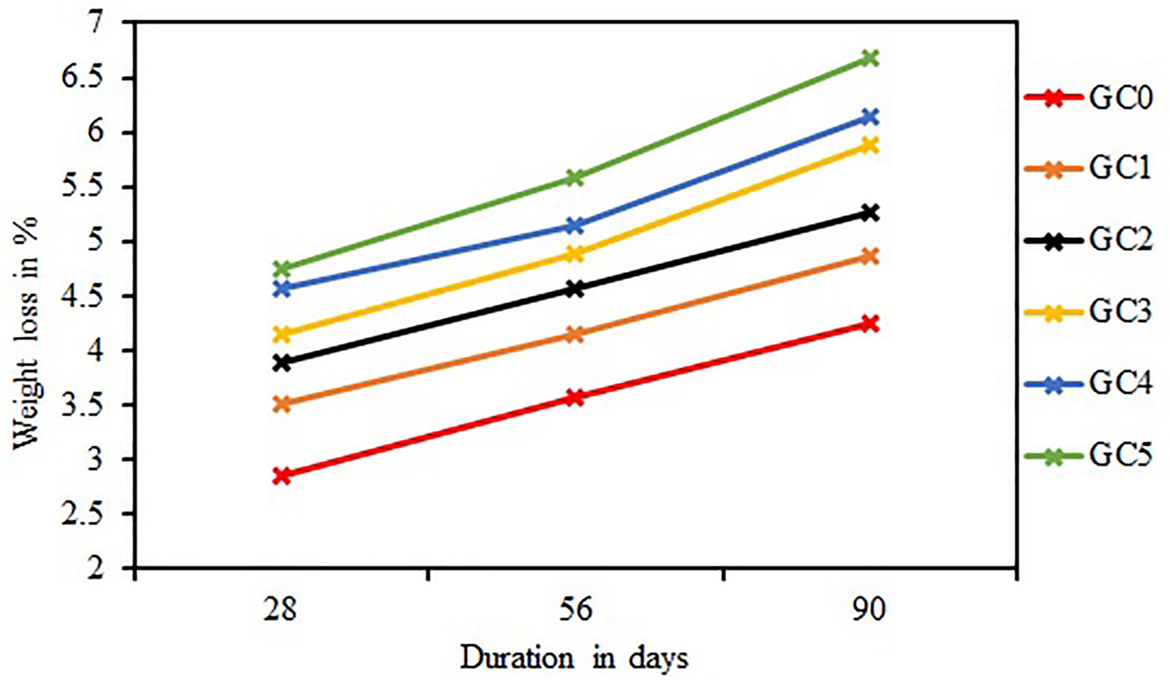

Figure 1: Percentage of weight loss in Acid resistance test.

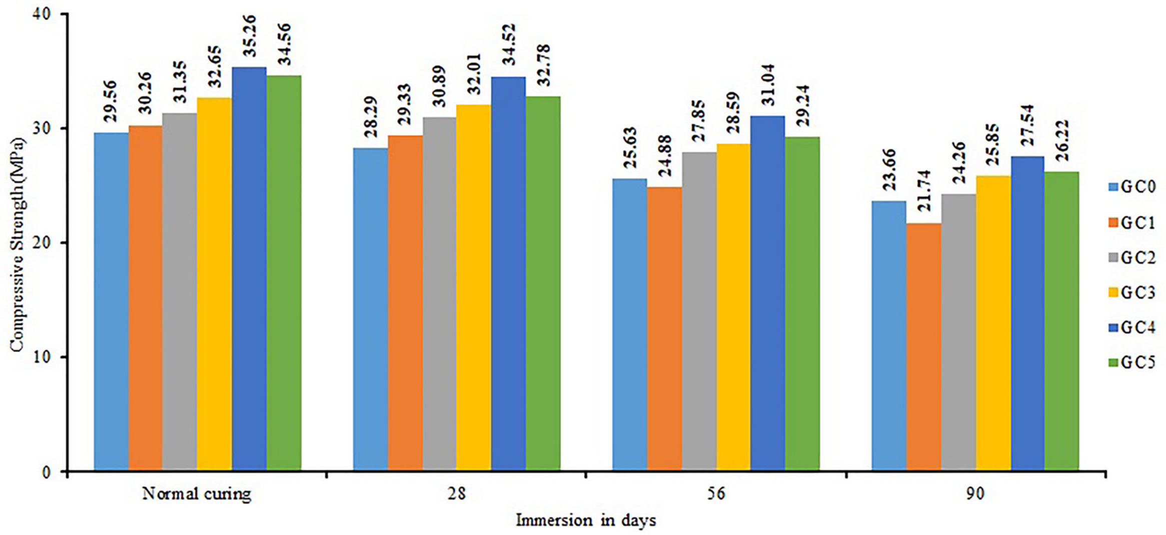

Figure 2: Variation of compressive strength after Acid resistance test.

In compressive strength test after acid resistance test result were compared with ambient curing specimens. The test result shows that maximum compressive strength of 35.26 MPa was estimated in GC4 mix in ambient curing. After 28 days of acid immersion, the compressive strength reduces to 34.52 MPa. The percentage differences are around 10% less than the ambient curing. The variation in CS after 56 and 90 days was recorded and it shows that very low compressive strength was estimated in GC1 compared with target mean strength. The orders of compressive strength loss are GC1 > GC2 > GC3 > GC5 > GC0 > GC4. The high dense siliceous layer was formed in geopolymer concrete due to the presence of calcium aluminium silicate gel. The binding between coconut shell with fly ash and GGBS are strong due to formation of gel in initial period of curing. The less acid attack was recorded in GC4 and stated that, optimal amount of replacement is 40% for conventional coarse aggregate.

4.3. Sulphate resistance test

The same as acid resistance test, sulphate resistance test was performed in the present study. In order to analysis the resistance capacity of coconut shell against sulphate ions, weight loss and compressive strength were performed. The weight loss of all mixes is shown in Figure 3. It represents that, weight loss percentage was increased with increase number of days. The low level of weight loss was measured in conventional geopolymer concrete and it is around 1% of weight loss. In coconut shell replacement concrete mixes, GC4 mix shows that weight loss percentage was reduce in 90 days, initially weight loss is greater than other mixes and increase in number of days, the weight loss was reduced. It indicates that, formation of siloxane bonds decreased the leaching effects of sulphate and act as a strong sulphate resistance concrete. The compressive strength of all mixes after sulphate resistance test was compared with normal curing method. In ambient curing, higher strength was obtained in GC4, GC3 mix compared with GC0. In sulphate acid curing, the compressive strength was gradually decreased

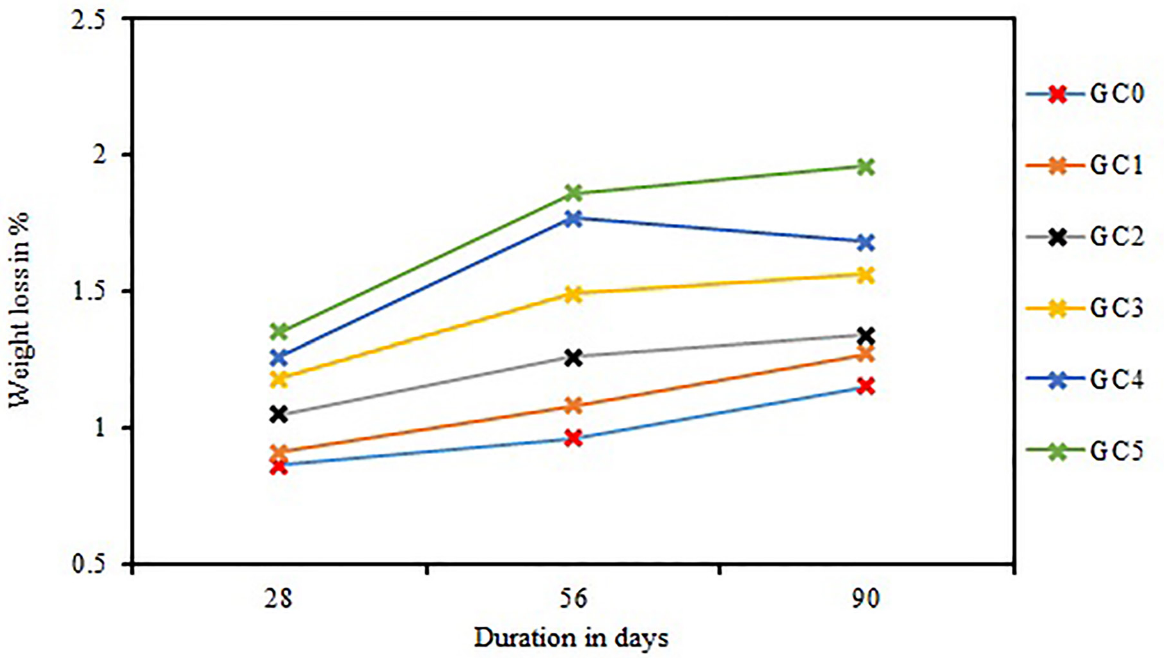

Figure 3: Percentage of weight loss in sulphate resistance test.

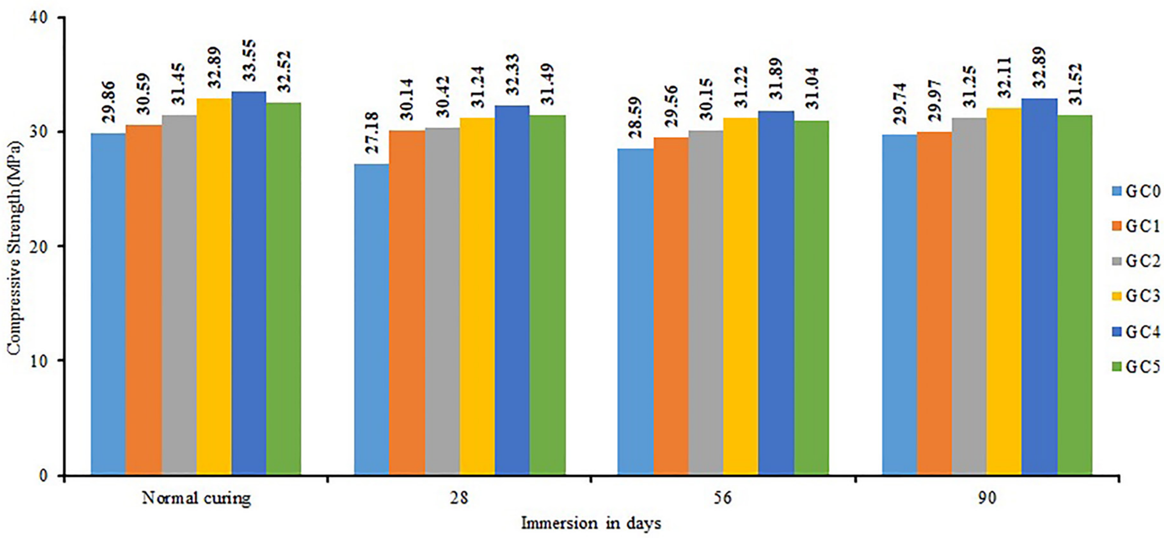

Figure 4: Variation of compressive strength after sulphate resistance test.

in 28 days, 56 days and 90 days. Around 10% of the strength was reduced after 56 days and 90 days respectively (Figure 4). In general, geopolymer concrete are good in sulphate attack and the present study evaluate the behaviour of coarse aggregate replaced by coconut shell and found that, 40% replacement of coconut shell act as high sulphate resistance compared with other mix.

4.4. RCPT

In general, increase the age of concrete will decrease the penetration of chloride into concrete. In the present study, RCPT test are shown in Figure 5. The average value of three specimen were taken in consideration and the results indicates that, all the mix were lies below the very low penetration level and also very low penetration was measured in the GC4 mix compared with other mix. The test results show that, 10% replacement of coconut shell has maximum level of penetration, 20%, 30% and 50% replacement have the equal level of penetration and 40% of the replacement has very low of penetration compared with other percentages and conventional mix. It indicates that, fly ash and GGBS act as binding material to increase the strength of the concrete and replacement of coarse aggregate by coconut shell also influenced the chloride penetration level. This test helps to understand the positive impact of replacement of coconut shell in the geopolymer concrete. The supplementing cementitious material with optimal level of coconut shell proven.

4.5. Water absorption capacity of concrete

To identify the optimal percentage of coconut shell replacement in geopolymer concrete and to assess the durability of the geopolymer as well, water absorption test results are more significant. The Figure 6 shows the variation of water absorption in three different time interval such as 28, 56 and 90 days. The results indicates that, increasing the days of immersion increase the percentage of water absorption in type of mix. At 28 days, maximum amount of 1.2% of water absorption was measured in 50% of the replacement of coconut shell and comparatively high percentage. At 56 days, conventional mix shows the low level of water absorption and GC5 shows the higher percentage of water absorption. At the end of 90 days, GC4 shows that very low level of water absorption compared with other mix concrete. The study found that, 40% optimal replacement of coconut shell gives the good durability property compared to conventional concrete.

4.6. Rate of absorption

Hall 1989 and Martys 1997 were performed the two different time variation of rate of absorption study such as 2 hrs and 24 hrs. In the present study, the rate of absorption was performed for 24 hrs and reading were measured every 10 minutes intervals. The test was performed for conventional and geopolymer concrete and test results

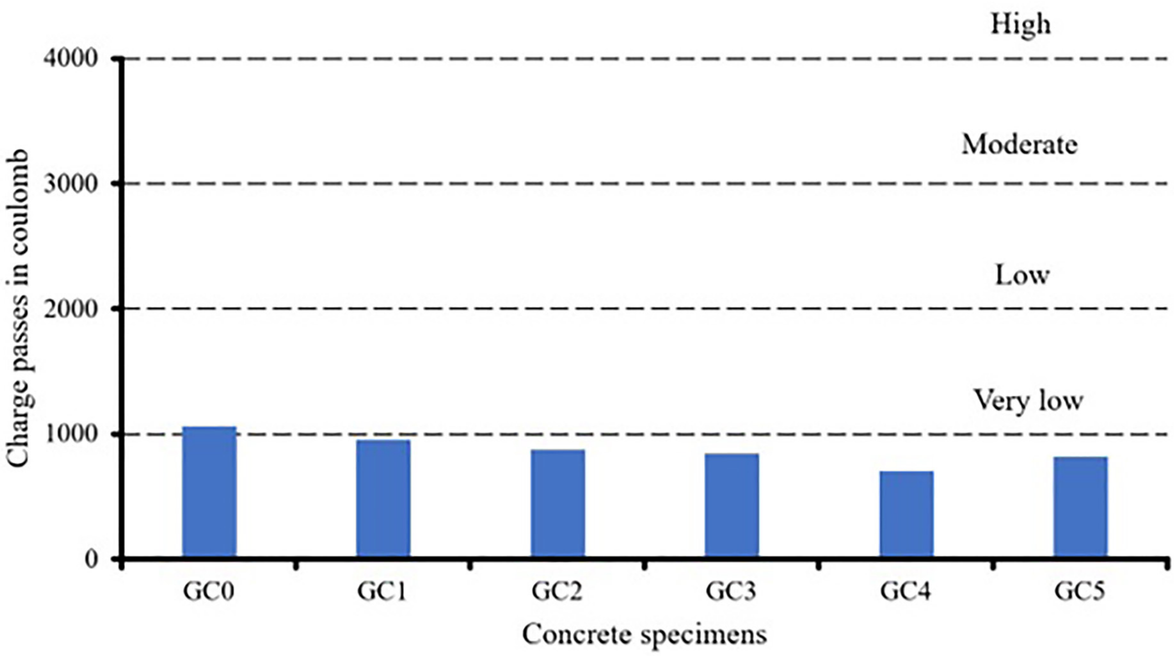

Figure 5: RCPT test result for different mix concrete.

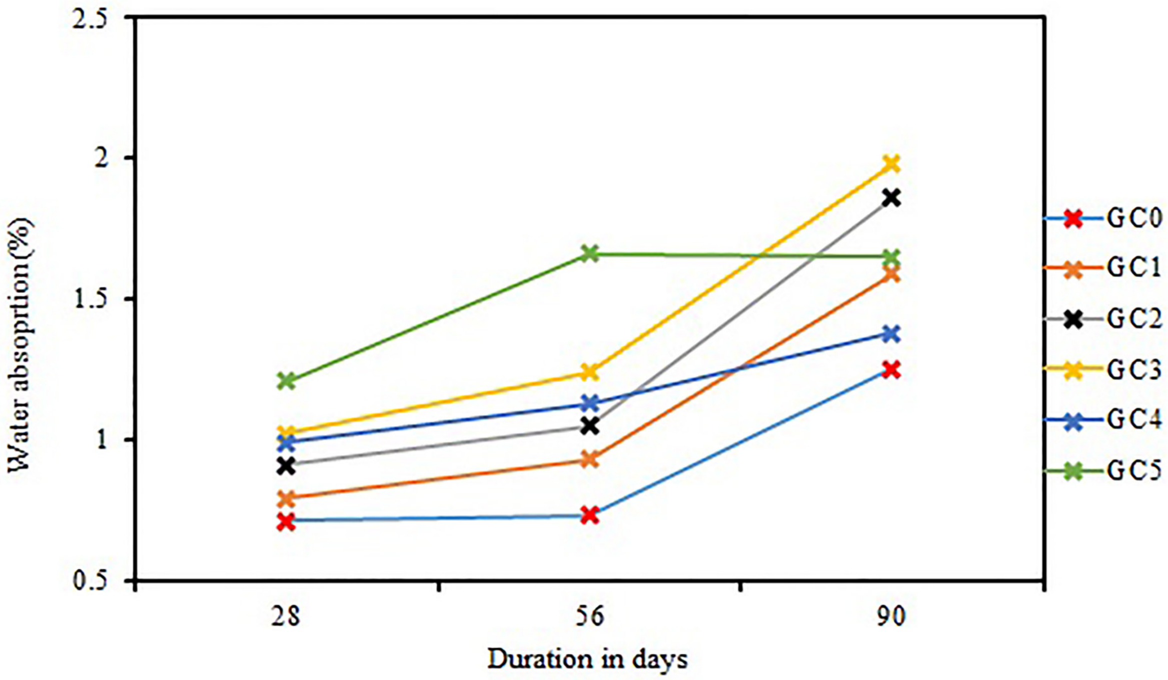

Figure 6: Water absorption of coconut shell based geopolymer concrete.

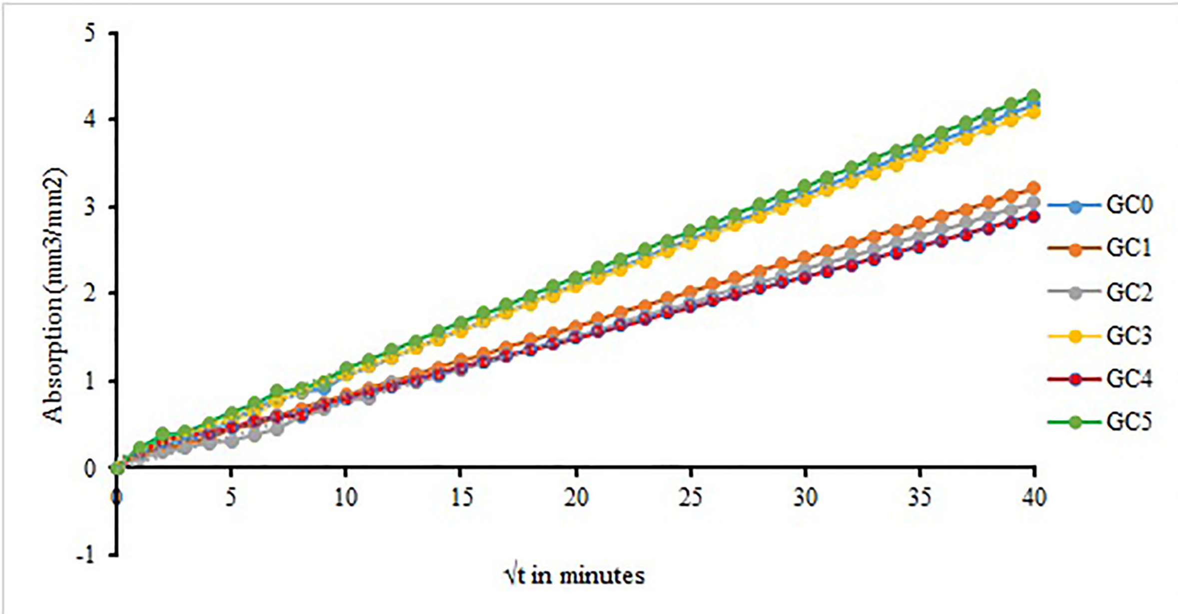

Figure 7: Rate of absorption test with respect to time.

are shown in fig. The regression analysis of time and absorption for all mix shows that, 0.996, 0.9997, 0.99, 0.9992, 0.9998 and 0.9991 for conventional, GC1, GC2, GC3, GC4 and GC5 (Figure 7). It indicates that, higher percentage of accuracy was achieved in GC4 mix. The rate of absorption in GC4 mix has high accuracy and very low error compared with other mix. The regression analysis results indicates that, fly ash and GGBS perfectly binding with coconut shell and optimal amount of replacement is 40% instead of conventional coarse aggregate. The rate of absorption of conventional is slightly higher than the geopolymer concrete and in geopolymer mix variation, GC4 has the very low rate of absorption compared with other mix.

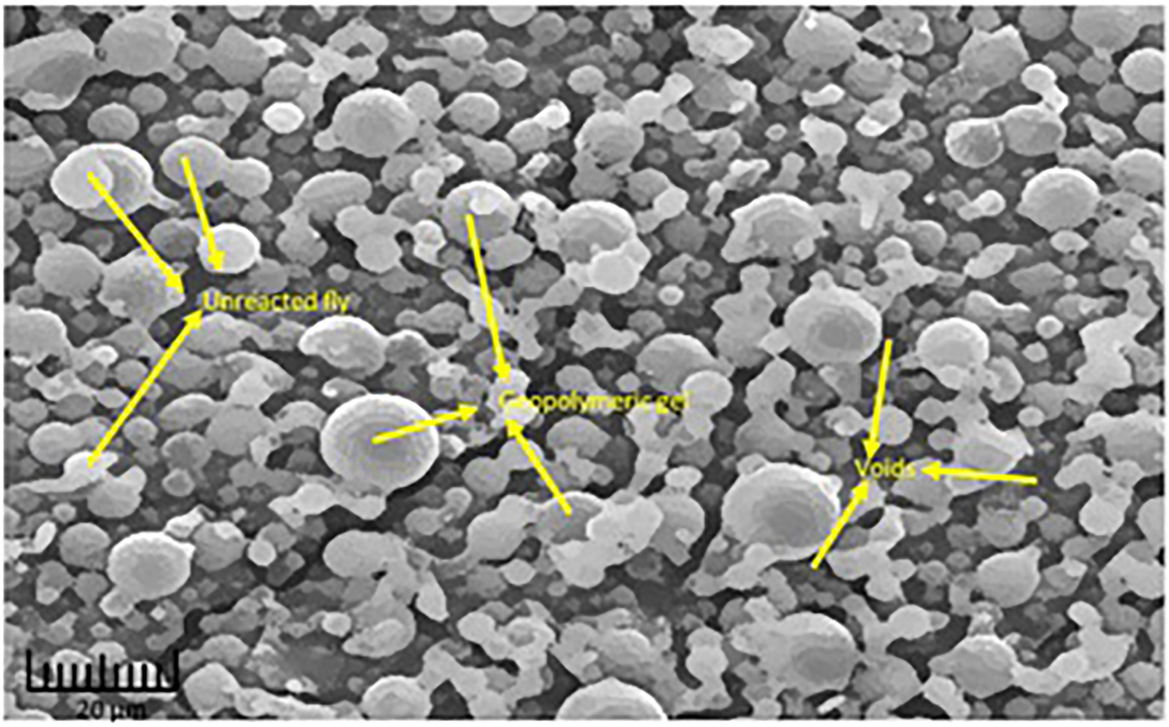

Figure 8: SEM analysis of coconut shell based geopolymer concrete.

4.7. Microstructure analysis

The microstructure analysis of geopolymer concrete confirmed the exact reaction between the fly ash and GGBS binding with coconut shell. In present study, the SEM result shows that, fly ash based geopolymer concrete contains calcium aluminosilicate hydrate gel while using fly ash and GGBS, the figure represents that, unreached fly ash and voids are present in the structure (Figure 8). The percentage of voids in the structure are the major reason for weight loss in acid and sulphate resistance test. Even in the water absorption and rate of absorption test also confirmed the effects of voids precent in the structure.

5. CONCLUSION

The novelty of the present study is to use coconut shell as coarse aggregate in fly ash based geopolymer concrete. The study results conclude that,

- The mechanical behaviour of geopolymer concrete shows that 40% replacement of coarse aggregate by coconut shell are high strength properties compared with other mix variations. About 10–15% of the high strength was achieved in GC4 mix.
- In acid and sulphate resistance test, conventional geopolymer concrete shows the better behaviour compared with coconut shell however GC4 mix shows the improved resistance property with increasing number of days. In 90 days, less amount of weight loss and good compressive strength was achieved in GC4 mix concrete.
- In RCPT test, all the mix concrete shows the very low level of chloride ion penetration and comparatively GC4 mix shows very low value of penetration. In water absorption and rate of absorption test, 40% replacement of coconut shell mix shows the low level of absorption and regression analysis shows that, 99% of the accuracy in the test result.

6. BIBLIOGRAPHY

[1] LIU, H., LI, Q., WANG, P., “Assessment of the engineering properties and economic advantage of recycled aggregate concrete developed from waste clay bricks and coconut shells”, *Journal of Building Engineering*, v. 68, pp. 106071, 2023. doi: http://doi.org/10.1016/j.jobe.2023.106071.

[2] AZIZ, W., ASLAM, M., EJAZ, M.F., *et al.*, "Mechanical properties, drying shrinkage and structural performance of coconut shell lightweight concrete", *Structures*, v. 35, pp. 26–35, 2022. doi: http://doi.org/10.1016/j.istruc.2021.10.092.

[3] SAHA, A.K., "Effect of class F fly ash on the durability properties of concrete", *Sustainable Environment Research*, v. 28, n. 1, pp. 25–31, 2018. doi: http://doi.org/10.1016/j.serj.2017.09.001.

[4] AMERICAN SOCIETY FOR TESTING AND MATERIALS, *Standard Test Method for Electrical Indication of concrete's Ability to Resist Chloride Ion Penetration*, Philadelphia, ASTM, 1997.

[5] AMERICAN SOCIETY OF TESTING AND MATERIALS, *ASTM C642. Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolana for Use as a mineral Admixture in Portland Cement concrete*, Am Soc Test Mater, Philadelphia, 1989.

[6] FAROOQ, F., AHMED, W., AKBAR, A., *et al.*, "Predictive modeling for sustainable high-performance concrete from industrial wastes: a comparison and optimi zation of models using ensemble learners", *Journal of Cleaner Production*, v. 292, pp. 126032, 2021. doi: http://doi.org/10.1016/j.jclepro.2021.126032.

[7] RANATUNGA, K.S., DEL REY CASTILLO, E., TOMA, C.L., "Evaluation of the optimal concrete mix design with coconut shell ash as a partial cement replacement", *Construction & Building Materials*, v. 401, pp. 132978, 2023. doi: http://doi.org/10.1016/j.conbuildmat.2023.132978.

[8] HASAN, N.M.S., SOBUZ, M.H.R., SHAURDHO, N.M.N., *et al.*, "Investigation of lightweight and green concrete characteristics using coconut shell aggregate as a replacement for conventional aggregates", *International Journal of Civil Engineering*, v. 22, pp. 1–17, 2023.

[9] AMERICAN SOCIETY FOR TESTING AND MATERIALS, *C1585-13: Sample Size to Estimate the Average Quality of a Lot or Process*, Philadelphia, ASTM, 1972.

[10] BABURAO, S.A., NEERAJA, B.M.D., "Sustainable al ternatives in concrete along with the use of medicinal plant Sapindus Mukoross i as a green workability agent", *Innov. Infrastruct. Solut.*, v. 6, n. 4, pp. 1–10, 2021.

[11] MOHAN, A., MINI, K.M., "Strength and durability studies of SCC incorporating silica fume and ultra fine GGBS", *Construction & Building Materials*, v. 171, pp. 919–928, 2018. doi: http://doi.org/10.1016/j.conbuildmat.2018.03.186.

[12] DIMITRIOU, G., SAVVA, P., PETROU, M.F., "Enhancing me chanical and durability properties of recycled aggregate concrete", *Construction & Building Materials*, v. 158, pp. 228–235, 2018. doi: http://doi.org/10.1016/j.conbuildmat.2017.09.137.

[13] THANGAPANDI, K., ANURADHA, R., AWOYERA, P.O., *et al.*, "Durability phenomenon in manufactured sand concrete: effects of zinc oxide and alcofine on behaviour", *Silicon*, v. 13, n. 4, pp. 1079–1085, 2021. http://doi.org/10.1007/s12633-020-00494-2.

[14] ORTEGA-LÓPEZ, V., FUENTE-ALONSO, J.A., SANTAMARÍA, A., *et al.*, "Durability studies on fiber-reinforced EAF slag concrete for pavements", *Construction & Building Materials*, v. 163, pp. 471–481, 2018. doi: http://doi.org/10.1016/j.conbuildmat.2017.12.121.

[15] LORENZO, J.K., ANDAL, A.R., MORALES, A.J., *et al.*, "Characterization of coconut husk ash as potential substitute for fly ash in geopolymer concrete", *Key Engineering Materials*, v. 963, pp. 145–151, 2023. doi: http://doi.org/10.4028/p-hY5Nkb.

[16] NITHYA, S., GUNASEKARAN, K., SANKAR, G., "A study on the flexural behaviour of geopolymer lightweight eco-friendly concrete using coconut shell as coarse aggregate", *Advances in Civil Engineering*, v. 2021, pp. 1–20, 2021. doi: http://doi.org/10.1155/2021/5534019.

[17] SHAHRABADI, H., NIKOO, H.S., FORSAT, M., "Effect of limestone on the mechanical properties of concrete containing silica fume and fly ash", *Journal of Materials and Environmental Sciences*, v. 8, n. 2, pp. 457–466, 2017.

[18] FORSAT, M., MIRJAVADI, S.S., HAMOUDA, A.M.S., "Investigation of the effect of Larestan's pipeline water on the mechanical properties of concretes containing granite aggregates", *Advances in Civil Engineering*, v. 2019, n. 1, pp. 4197186, 2019. doi: http://doi.org/10.1155/2019/4197186.

[19] MIRJAVADI, S.S., FORSAT, M., YAHYA, Y.Z., *et al.*, "Analysis of post-buckling of higher-order graphene oxide reinforced concrete plates with geometrical imperfection", *Advances in Concrete Construction*, v. 9, n. 4, pp. 397–406, 2020.

[20] PARAMASIVAM, S.K., RAJENDRAN, S., "Experimental investigation on mechanical behavior of geopolymer light weight concrete", *Matéria (Rio de Janeiro)*, v. 28, n. 3, pp. e20230160, 2023. doi: http://doi.org/10.1590/1517-7076-rmat-2023-0160.

[21] IKPONMWOSA, E.E., EHIKHUENMEN, S., EMESHIE, J., *et al*., "Performance of coconut shell alkali-activated concrete: experimental investigation and statistical modelling", *Silicon*, v. 13, n. 2, pp. 335–340, 2021. doi: http://doi.org/10.1007/s12633-020-00435-z.

[22] KUMAR, V.R.P., GUNASEKARAN, K., SHYAMALA, T., "Char acterization study on coconut shell concrete with partial replacement of cement by GGBS", *Journal of Building Engineering*, v. 26, pp. 100830, 2019. doi: http://doi.org/10.1016/j.jobe.2019.100830.

[23] HASAN, N.M.S., SOBUZ, M.H.R., SHAURDHO, N.M.N., *et al*., "Investigation of lightweight and green concrete characteristics using coconut shell aggregate as a replacement for conventional aggregates", *International Journal of Civil Engineering*, v. 22, n. 1, pp. 37–53, 2024. doi: http://doi.org/10.1007/s40999-023-00881-x.

[24] CHANDRAN, K.P., NATRAJAN, M., MEIARAJ, C., "Impact resistance of Fly ash based geo polymer concrete using coconut shell aggregate", *International Journal of Civil Engineering and Technology*, v. 7, n. 5, pp. 292–303, 2016.

[25] ABBASS, M., SINGH, D., SINGH, G., "Properties of hybrid geopolymer concrete prepared using rice husk ash, fly ash and GGBS with coconut fiber", *Materials Today: Proceedings*, v. 45, pp. 4964–4970, 2021. doi: http://doi.org/10.1016/j.matpr.2021.01.390.

[26] SAMADHI, T.W., WULANDARI, W., SUROTO, A., *et al*., "Synthesis of geopolymer from blends of tropical biomass ashes", *IOP Conference Series. Materials Science and Engineering*, v. 622, n. 1, pp. 012034, Oct. 2019. doi: http://doi.org/10.1088/1757-899X/622/1/012034.

[27] JAGADEEP, K., NAGARAJU, T.V., CHAITANYA, M.S.K., *et al*., "Effective utilization of agricultural ashes in development of sustainable geopolymer concrete", *Materials Today: Proceedings*, 2023. doi: http://doi.org/10.1016/j.matpr.2023.05.447.

[28] SAMADHI, T.W., WULANDARI, W., PRASETYO, M.I., *et al*., "Reuse of coconut shell, rice husk, and coal ash blends in geopolymer synthesis", *IOP Conference Series. Materials Science and Engineering*, v. 248, n. 1, pp. 012008, Oct. 2017. doi: http://doi.org/10.1088/1757-899X/248/1/012008.

[29] WEI, J., YING, H., YANG, Y., ZHANG, W., YUAN, H. ZHOU, J., (2023). "Seismic performance of concrete-filled steel tubular composite columns with ultra high performance concrete plates", *Engineering Structures*, v. 278, pp. 115500, 2023. doi: https://doi.org/10.1016/j.engstruct.2022.115500

[30] SUN, L., WANG, C., ZHANG, C., *et al*., "Experimental investigation on the bond performance of sea sand coral concrete with FRP bar reinforcement for marine environments", *Advances in Structural Engineering*, v. 26, n. 3, pp. 533–546, 2023. doi: 10.1177/13694332221131153

[31] CUI, D., WANG, L., ZHANG, C., *et al*., "Dynamic Splitting Performance and Energy Dissipation of Fiber-Reinforced Concrete under Impact Loading", *Materials* , v. 17, n. 2, pp. 421, 2024. doi: https://doi.org/10.3390/ma17020421

[32] HUANG, H., HUANG, M., ZHANG, W., *et al*., "Experimental Investigation on Rehabilitation of Corroded RC Columns with BSP and HPFL under Combined Loadings", *Journal of Structural Engineering*, v. 146, n. 8, pp.1–18, 2020. doi: 10.1061/(ASCE)ST.1943-541X.0002725

[33] HUANG, H., GUO, M., ZHANG, W., *et al*., "Numerical investigation on the bearing capacity of RC columns strengthened by HPFL-BSP under combined loadings", *Journal of Building Engineering*, v. 39, pp. 102266, 2021. doi: https://doi.org/10.1016/j.jobe.2021.102266

[34] HUANG, H., YUAN, Y., ZHANG, W., *et al*., "Property Assessment of High-Performance Concrete Containing Three Types of Fibers", *International Journal of Concrete Structures and Materials*, v. 15, n. 1, pp. 39, 2021. doi: 10.1186/s40069-021-00476-7

[35] ZHANG, W., LIN, J., HUANG, Y., *et al*., "Temperature-dependent debonding behavior of adhesively bonded CFRP-UHPC interface", *Composite Structures*, v. 340, pp. 118200, 2024. doi: https://doi.org/10.1016/j.compstruct.2024.118200

[36] LI, Z., GAO, M., LEI, Z., *et al*., "Ternary cementless composite based on red mud, ultra-fine fly ash, and GGBS: Synergistic utilization and geopolymerization mechanism", *Case Studies in Construction Materials*, v. 19, pp. e2410, 2023. doi: https://doi.org/10.1016/j.cscm.2023.e02410

[37] YAO, X., LYU, X., SUN, J., *et al*., "AI-based performance prediction for 3D-printed concrete considering anisotropy and steam curing condition", *Construction and Building Materials*, v. 375, pp. 130898, 2023. doi: https://doi.org/10.1016/j.conbuildmat.2023.130898

[38] FANG, B., QIAN, Z., SONG, Y., *et al*., "Evaluation of early crack resistance performance of concrete mixed with ternary minerals using temperature stress testing machine (TSTM)", *Journal of Cleaner Production*, v. 465, pp. 142780, 2024. doi: https://doi.org/10.1016/j.jclepro.2024.142780

[39] WEI, C., LI, Y., LIU, X., *et al*., "Large-scale application of coal gasification slag in nonburnt bricks: Hydration characteristics and mechanism analysis", *Construction and Building Materials*, v. 421, pp. 135674, 2024. doi: https://doi.org/10.1016/j.conbuildmat.2024.135674

[40] KE, G., LI, Z., JIANG, H. (2024). "Study on long-term solidification of all-solid waste cementitious materials based on circulating fluidized bed fly ash, red mud, carbide slag, and fly ash", *Construction and Building Materials*, v. 427, pp. 136284, 2024. doi: https://doi.org/10.1016/j.conbuildmat.2024.136284

[41] JIN, Z., LI, M., PANG, B., *et al*., "Internal superhydrophobic marine concrete: Interface modification based on slag microstructure regulation", *Journal of Building Engineering*, v. 86, pp. 108769, 2024. doi: https://doi.org/10.1016/j.jobe.2024.108769