KSCE Journal of Civil Engineering (2023) 27(4):1708-1719
DOI 10.1007/s12205-023-1072-2

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Structural Engineering

Strength and Durability Evaluation of Multi-Binder Geopolymer Concrete in Ambient Condition

Jay Bhavsar[a] and **Vijay R. Panchal**[a]

[a]*Dept. of Civil Engineering, Chandubhai S. Patel Institute of Technology (CSPIT), Faculty of Technology & Engineering (FTE), Charotar University of Science and Technology (CHARUSAT), Changa-388421, Gujarat, India*

ARTICLE HISTORY

Received 14 June 2022
Revised 11 November 2022
Accepted 9 January 2023
Published Online 28 February 2023

KEYWORDS

Acid resistance
Impermeability
Young's modulus
Waste recycling
Workability
Split tensile strength

ABSTRACT

In recent decades, researchers have been fascinated with geopolymer concrete because of its minimal carbon footprint. Geopolymer concrete (GPC) has been found a viable alternative for recycling industrial waste. The efficient use of these wastes in geopolymer concrete reduces environmental pollution. In the study, three industrial wastes were utilized for making geopolymer concrete at ambient temperature. These wastes are fly ash, ground granulated blast furnace slag (GGBS), and two different ceramic polishing waste (CPW). The study proposes fly ash as the primary binder. GGBS is projected as the additive for ambient curing, and CPWs as a recycling binder. The alkali activators Na_2SiO_3 and NaOH were used to manufacture the concrete mixture consisting of three binders. Important GPC factors such as workability, mechanical strength, sorptivity, water absorption, acid resistance, and chloride resistance have been examined. Further Carbon footprint is also measured to know the environmental impact. The findings revealed an improvement in capillary porosity and chloride permeability with the increase of CPWs upto 20%. The SEM images revealed improvement in microstructure with an increase in CPWs upto 20%. The use of CPWs also reduced the Carbon footprint of GPC. The study determined that the mechanical, durability and environmental qualities of multi-binder GPC make it suitable for structural concrete.

1. Introduction

The growth of the construction industry created a high demand for cement. To reduce CO_2 footprint low carbon materials are desirable for sustainable construction. The CO_2 emissions as a result of cement production are about 7% of the total emissions at a global level (Huseien et al., 2019). Geopolymer has a low CO_2 footprint compared to Portland cement (Davidovits, 1993). It is an emerging research field where large amounts of industrial wastes and agricultural wastes can be utilized (Khale and Chaudhary, 2007). Geopolymer is obtained by the synthesis of alumino-silicate materials with alkaline solutions. The geopolymer concrete or mortar is developed at an ambient or higher temperature. Temperature curing restricts the application of fly ash-based GPC in on-site concreting (Nath and Sarker, 2014). Nevertheless, calcium-based source materials like GGBS, Portland cement, and High calcium fly ash give high strength at room temperature (Nath and Sarker, 2014). On the other hand, the alkali activation of high calcium-based materials like GGBS is considered alkali-activated concrete, which is different from geopolymer concrete (Davidovits, 2018).

Demand for ceramic tiles has increased substantially in the past decades and will increase in the future. The production of ceramic tiles produces ceramic polishing wastes through the polishing process. Approximately 1.9 kg of ceramic waste was generated out of one cubic meter of polished tiles (El-Dieb et al., 2018). These wastes are not recycled and disposed of for landfilling. These wastes create land, water, and air pollution in the surrounding environment. Additionally, the disposal of CPWs require huge land resources. Recycling these wastes in GPC has many advantages, like cost reduction, environmental protection, and energy savings. In the past, the CPW was successfully utilized as a cement replacement. However, the use of CPW in GPC is at the preliminary stage.

The geopolymer bricks were developed using fine cyclone waste found in the ceramic tile industry (Amin et al., 2017). The authors claimed a maximum strength of 10 MPa after 90 days of

CORRESPONDENCE Jay Bhavsar jaybhavsar.cv@charusat.ac.in Dept. of Civil Engineering, Chandubhai S. Patel Institute of Technology (CSPIT), Faculty of Technology & Engineering (FTE), Charotar University of Science and Technology (CHARUSAT), Changa-388421, Gujarat, India

room curing. Inversely, curing at higher temperatures reduces strength. Aly et al. (2018) explored the possibility of producing GPC for CPW and GGBS. The samples are cured at 60ºC for 24 hours. The authors concluded that CPW demands a high amount of superplasticizer for flowability.

In some literature, ceramic waste powder (C-W-P) is obtained by crushing ceramic tiles and used as a geopolymer binder (Huseien et al., 2018; Shoaei et al., 2019; Huseien et al., 2020; Shah and Huseien, 2020). "Shoaei et al. (2019) prepared a geopolymer mortar with 100% C-W-P". "The optimum alkaline solution to binder ratio for geopolymer mortar was found to be 0.6, and the optimum curing temperature was obtained at 90ºC." Kaya (2021) produced geopolymer paste using raw ceramic powder(CP). The micro SiO_2 and Al_2O_3 were used as additives to enhance mechanical properties. An oven curing at 105 °C was adopted. The strength was increased with the increase of SiO_2/Al_2O_3 and the $(SiO_2 + Al_2O_3)$/CP ratio in the sample. Another study by Kaya (2022) reported the use of CP for making geopolymer mortar activated by NaOH and Na_2SiO_3. NaOH with different proportions of Na by binder weight was employed. The silicate modulus of the activator was set at 0 to 0.3 with an increment of 0.1. The result found that increased silicate modulus reduced the mechanical performance while increasing Na with low water content improved mechanical strength. Ameri et al. (2019) found that a C-W-P-based lightweight geopolymer mortar worked best when the temperature was high.

Huseien et al. (2020) prepared alkali-activated self-compacting concrete (SCC) by using C-W-P and GGBS. The flow and passing ability improved with the increase of C-W-P while segregation resistance decreased. The addition of C-W-P also improved sulfuric acid resistance.

According to the literature, previous studies focused on alkali-activated mortar with C-W-P replacing GGBS. In most of the studies, the strength was achieved through GGBS (more than 50%) or temperature curing. More GGBS produces calcium-based reaction products and less geopolymer gel. The past studies focused on mechanical performance on mortar or paste and very few on concrete (aggregate large than 6 – 10 mm). Also, there is a need to study the mechanical and durability performance of GPC at the site scale where concrete is cast at the site at ambient temperature. As far as best of our information, no studies have been reported on GPC made of fly ash, GGBS, and CPW at ambient curing. Also in the study fly ash is replaced by CPW and low GGBS content is used. Moreover, the CPW used for this study was in sludge form that required less energy for crushing than C-W-P which was made by crushing ceramic tiles.

The study developed multi-binder GPC using fly ash, GGBS, and CPW. Two types of CPWs were studied. The GPC is made at ambient temperatures of 23°C to 25°C, ensuring its use in actual construction practice. The objectives are to produce concrete that is economical, strong, durable, and environment-friendly. The CPWs were used for the economy, and a lower alkaline-to-binder ratio was used for strength. The strength and durability effects of CPWs on the fly ash replacement were examined. The environmental impact was evaluated by measuring the carbon emissions for GPC production. The evaluation satisfied the strength and durability requirements for M35-grade structural concrete. The results will be useful for making concrete that is good for the environment and lessens the bad effects of CPW disposal.

2. Materials

CPWs are obtained through the ceramic tile industry in sludge form (Fig. 1). Two types of waste were obtained: vitrified ceramic polishing waste (VCPW) and wall tile ceramic polishing waste (WCPW). As obtained wastes contain moisture, it was heated for a day at 110ºC to remove the moisture. To bring it in uniform powder wastes were crushed in a ball mill. The specific surface area of VCPW and WCPW (CPWs), fly ash, and GGBS is measured by Blain's air permeability method (ASTM C204-11, 2011) (Table 1). The chemical properties of fly ash, CPWs, and

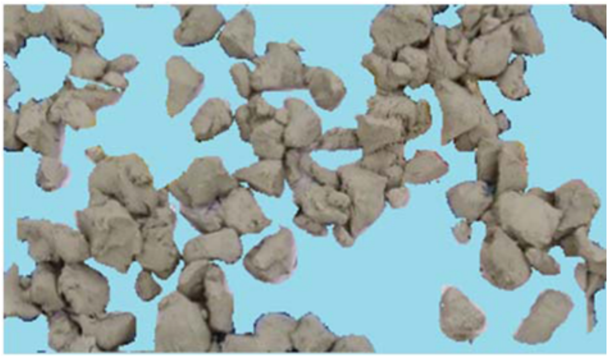

Fig. 1. Raw Ceramic Polishing Waste

Table 1. Physical Properties of Binders

Binder	Fly ash	VCPW	WCPW	GGBS
Specific Surface Area (m^2/kg)	553.8	497.6	557.8	448.1
Specific Gravity	2.500	2.529	2.530	2.88

Table 2. Chemical Properties of Binders

Metal Oxide	Fly ash	VCWP	WCWP	GGBS
	% mass			
SiO_2	58.98	70.71	57.55	35.41
Al_2O_3	15.18	11.56	11.55	17.60
Fe_2O_3	12.58	02.86	07.77	01.62
CaO	01.82	03.45	10.86	37.58
MgO	00.62	01.21	01.68	07.60
Na_2O	00.25	01.39	00.96	-
K_2O	01.88	03.39	01.50	-
SO_3	01.60	00.46	02.88	00.75
P_2O_5	00.58	00.16	00.28	-
TiO_2	03.98	01.48	02.45	-
ZnO	00.20	01.17	01.23	-
LOI	01.20	00.66	02.33	00.91

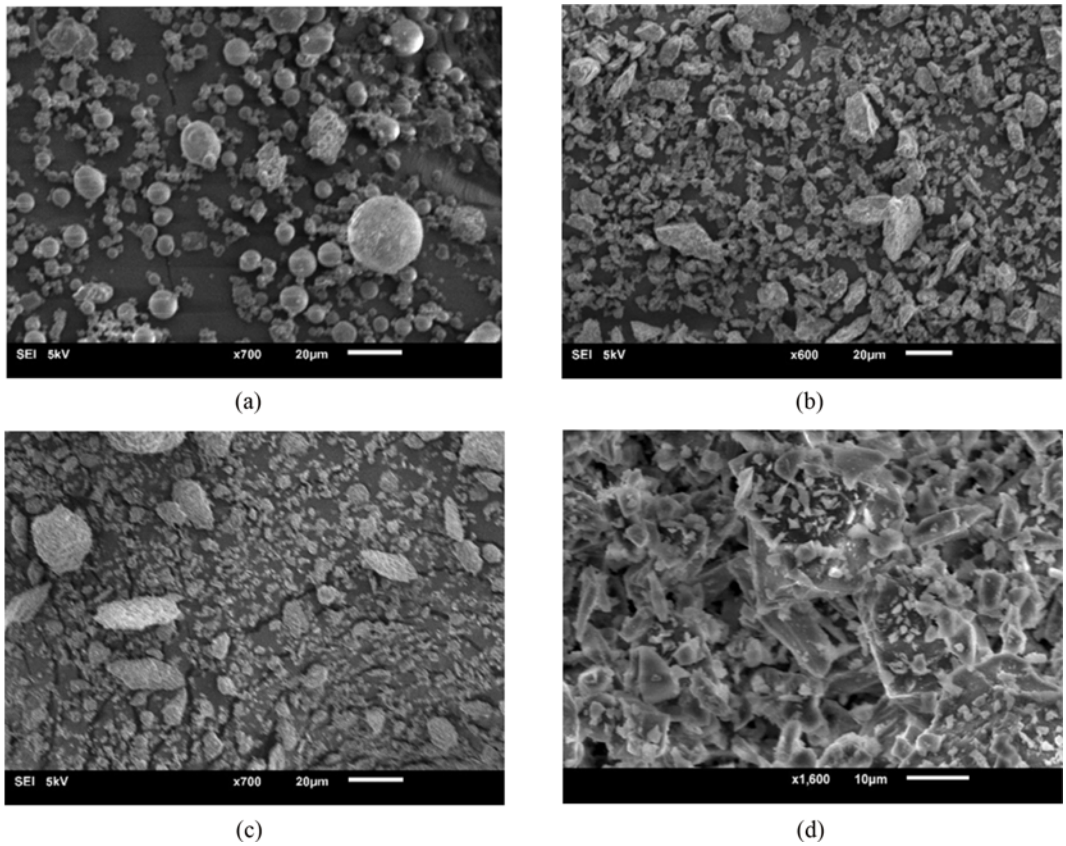

Fig. 2. SEM Image: (a) Fly Ash, (b) VCPW, (c) WCPW, (d) GGBS

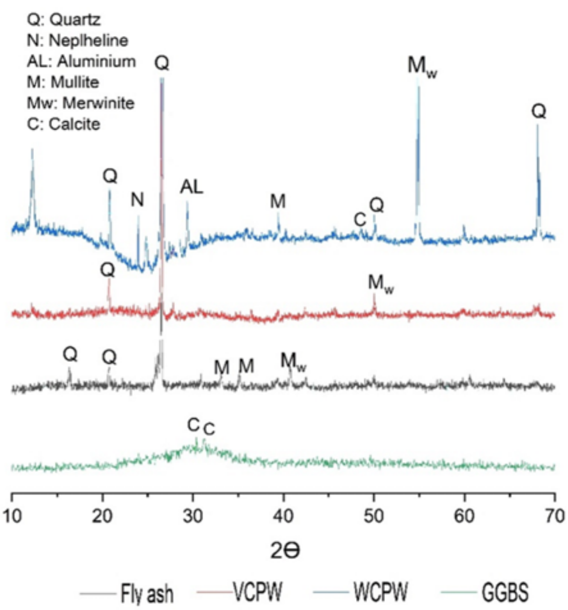

Fig. 3. XRD of Binders

GGBS were investigated through the X-ray fluorescence method (Table 2). Scanning Electron Microscope (SEM) images were obtained for all binders (Fig. 2). The shape of fly ash particles is spherical (Fig. 2(a)), while it is angular for CPWs (Figs. 2(b) and 2(c)) and GGBS (Fig. 2(d)).

Table 3. Crstallinity Index

Binder	Fly ash	VCPW	WCPW	GGBS
Crystallinity Index (CI)	20.50	11.20	28.52	10.21

The crystalline phases were identified by the X-ray diffraction (XRD) method (Fig. 3). The crystallinity index for all binders was derived from the ratio of integrated areas of crystalline peaks to the combined integrated area of crystalline and amorphous peaks (Table 3). The lower crystalline index indicates the availability of an amorphous phase in the binder. The results of XRD and XRF confirm the existence of high silica in fly ash, VCPW, and WCPW, while a high amount of CaO is found in GGBS. Amorphous silica in fly ash, VCPW, and WCPW can produce geopolymer gel. The presence of amorphous calcite in GGBS may produce tobermorite (C-S-H) gel.

For the experiment, coarse aggregates (CA) with sizes of 20 and 10 mm were combined with fine aggregates (FA). The fine aggregates were selected with a fineness modulus of 2.56 and Zone II as per the Indian standard (IS). The fine and coarse aggregates had specific gravity values of 2.6 and 2.69, respectively. Both aggregates were graded as per the requirements of IS 383 (2016). The aggregate grading curves are presented in Fig. 4.

Commercially available technical-grade sodium hydroxide (NaOH) flakes were used in the study. A NaOH 14 M solution

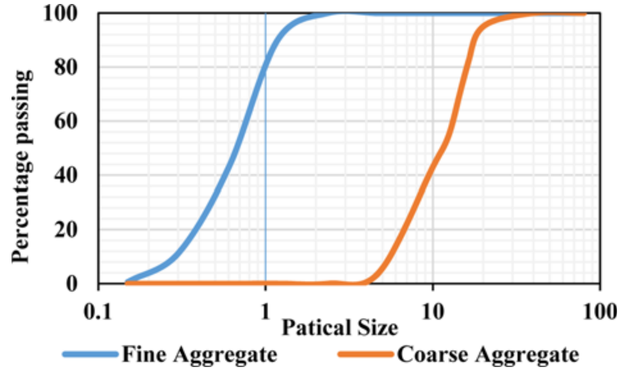

Fig. 4. Grading of Aggregates

was prepared considering past studies (Kumar et al., 2017). Sodium silicate (Na_2SiO_3) was purchased at a 1.97 SiO_2 to Na_2O proportion by mass. The SiO_2, Na_2O, and water percentages in the Na_2SiO_3 were 31.4%, 15.9%, and 52.7%, respectively.

2.1 Methods

The GPC mixes were created by referring to past studies (Lloyd and Rangan, 2010). The aggregate proportions were taken as 77% of the overall concrete mass. All mixes were made with a 0.35 alkaline liquid-to-binder ratio and a 2.5 Na_2SiO_3/NaOH ratio. Extra water and admixtures were added to increase workability. The amount of GGBS that is contained in each mix remains the same, while CPWs were used to partly substitute fly ash in amounts ranging from 15 to 20 percent by weight (Table 4). The samples are cured at ambient temperature. For each set of tests, three specimens were separated from different batches.

The target strength for GPC is calculated 43.25 MPa for M35 grade concrete as per IS 10262 (2019). The important concrete properties were measured as per the relevant standard (Table 5).

3. Result and Discussion

3.1 Workability of GPC

The flow of concrete is a vital parameter for on-field applications. The workability findings describe the decrease in slump value as CPWs increase (Fig. 5) or decreasing fly ash significantly affects concrete flow. Fly ash particles have better flowability than slag and CPW particles due to their spherical shape (Fig. 2). As a result, the base mix saw a high slump. The mix of SGV15 and SGW15 showed a high slump compared to SGV20 and SGW20.

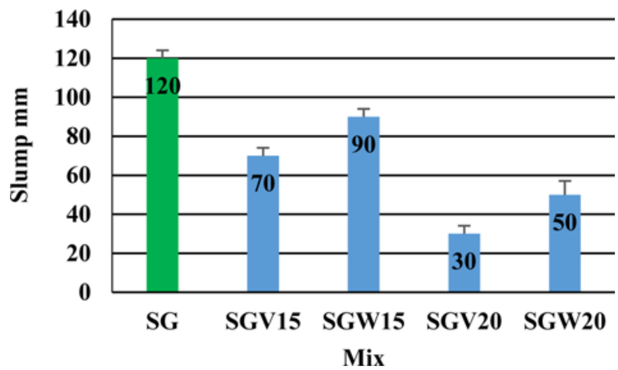

Fig. 5. Slump of GPC

Table 4. GPC Mixes

Mix	Aggregates			Binders			Alkaline Solution		Admixtures	Si/Al
	CA		FA	Fly Ash	GGBS	CPW	Na_2SiO_3	NaOH		
	20 mm	10 mm								
SG	610	406	832	327.11	81.77	-	102.22	40.89	-	2.55
SGV15	610	406	832	278.05	81.77	49.06[a]	102.22	40.89	-	3.18
SGW15	610	406	832	278.05	81.77	49.06[b]	102.22	40.89	-	3.40
SGV20	610	406	832	261.60	81.77	65.42[a]	102.22	40.89	6.13	3.55
SGW20	610	406	832	261.60	81.77	65.42[b]	102.22	40.89	6.13	3.77

Mixture: SGC-Fly ash + GGBS Geopolymer Concrete, Vx-Percentage of VCPW, Wx-Percentage of WCPW, [a]VCPW, [b]WCPW, CA-Coarse Aggregates, FA-Fine aggregates

Table 5. Test Procedures

Sr. No.	Name of Concrete Properties	Relevant Standard	Specimen Size
1	Workability by slump come	IS 1199 (2018)	-
2	Compressive Strength	IS 516 (Part 1/Sec 1) (2021)	150 mm cube
3	Split Tensile strength		150 mm diameter cylinder and 300 height
4	Modulus of Elastisity (MOE)	IS 516 (Part 8/Sec 1) (2020)	150 mm diameter cylinder and 300 mm height
5	Sorptivity Test	ASTM 1585-13 (2013)	100 mm diameter cylinder and 50 mm height
6	Acid resistance	-	150 mm cube
7	Chloride penetration test	ASTM C1202-19 (2019)	100 mm diameter cylinder and 50 mm height
8	Water absorption test	ASTM C642-13 (2013)	100 mm diameter cylinder and 50 mm height

This happened due to the water-absorbent nature and the high water demand of CPWs. Previous research found that increasing the C-W-P in place of GGBS increases the flow of geopolymer concrete (Huseien et al., 2018; Huseien et al., 2020). Hence, GGBS demands more water than CPWs. However, the present study implies that CPWs demand more water than fly ash. Nath and Sarker (2014) reported a decreased slump value for fly ash-based GPC when GGBS content was increased. Hence, fly ash is a more satisfactory binder for workability than GGBS and CPWs. Adding admixture or increasing alkaline activator can improve workability, but it may also increase costs.

3.2 Compressive Strength of GPC

Three cubes from different batches were tested for each design at 3, 7, 28, and 56 days for the investigation of compressive strength. The average results are presented for the discussion (Fig. 6). At 28 and 56 days, the compressive strength of all the mixtures exceeded the target strength i.e. 43.25 MPa (Fig. 6). The compressive strength presented here is cube strength and equivalent targeted cylindrical strength is 34.6 MPa. The cube strength is converted into cylindrical strength as per the factor suggested in IS 516 (Part 1/Sec 1) (2021). The strength of 43 – 50 MPa is achieved through an optimum molar solution (14M), a lower alkaline-to-binder ratio (0.35), and a 20% GGBS content. Aly et al. (2017) reported 14M NaOH resulted in the highest compressive strength for ceramic waste-based geopolymer mortar. Fly ash and slag-based GPC with a 0.35 A/B ratio gives high compressive strength at ambient curing (Nath and Sarker, 2014).

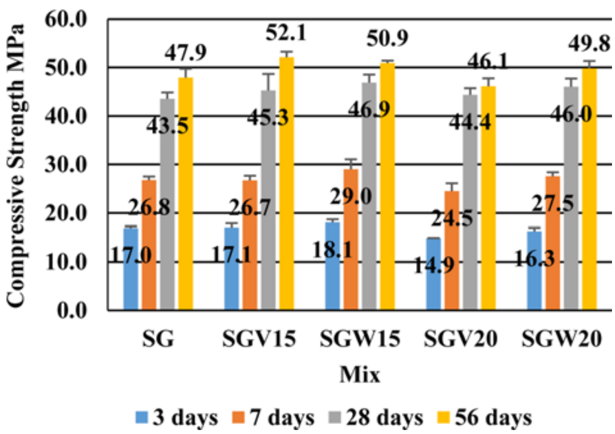

Fig. 6. Compressive Strength of GPC

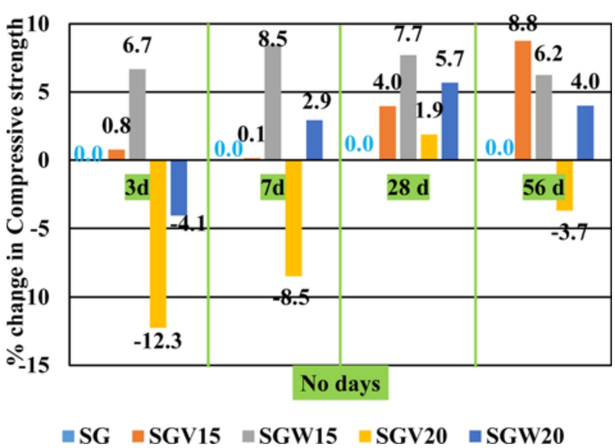

Fig. 7. % Change in Compressive Strength Compared to SG Mix

Both the SGV15 and SGW15 mixes increased in strength than the SG mix at 28 and 56 days (Figs. 6 and 7). This increment in later strength confirms the formation of geopolymer gel/ aluminosilicate because of CPWs. The reactivity of ceramic waste is significant at a later stage (Aly et al., 2017). Chindaprasirt and Rattanasak (2017) reported increased compressive strength of high calcium fly ash geopolymers with time, owing to the formation of CSH and aluminosilicate in composites.

The percentage change in compressive strength of each mix is compared with the base mix SG (Fig. 7). Three and seven days' compressive strength for SGW15 was increased by 6.67% and 8.46%. The SGV15 showed 0.77% and 0.14% increase in compressive strength at 3 and 7 days. The increase in early age strength for mix SGW15 is due to high CaO in WCPW than VCPW (Table 1 and Fig. 3). The early compressive strength of fly ash geopolymer improved due to calcium-bearing compound in the slag (Nath and Sarker, 2014). However, SGW20 shows lower strength -12.25 % at 3 days compared to the SG mix but at 7 days' strength was 2.92% higher than the SG mix (Fig. 7). The additional admixture in SGW20 slowed down the setting and hardening processes at an early age, so the strength was lower at 3 and 7 days. SGV20 showed a minor reduction (3.71%) at 56 days compared to the SG mix. Also, the strength of SGV20 was slightly lower than that of SGV15 (Fig. 7). The compressive strengths were slightly reduced because of slow polymerization during ambient curing, the low reactivity of CPW, and the uniformity of CPW. Aly et al. (2018) reported that the inclusion of slag in CPW geopolymer can boost or reduce compressive strength at ambient temperature. The presence of CPWs enhanced the Si/Al ratio and, hence, compressive strength was improved (Table 4) for the rest of the mix at 28 and 56 days. The change in the ratio of Si/Al caused by C–W–P can affect the compressive strength of the composite (Rashad and Essa, 2020).

Zhang et al. (2021) reported an increase in the strength of alkali-activated paste as C-W-P increased up to 20%. In addition, the C-W-P increased thermal resistance and decreased the deterioration of the samples. Huseien et al. (2018) reported that C-W-P increased resistance to high temperatures. The strength of the alkali-activated paste amplified when 0 to 50% GGBS was replaced by ceramic wastes (Rashad and Essa, 2020). In contrast, the strength of the alkali-activated system was decreased when GGBS was replaced by C-W-P (Huseien et al., 2018; Abdollahnejad et al., 2019; Huseien et al., 2019).

3.3 Split Tensile Strength of GPC

Split tensile strength is a crucial property of concrete. The essential concrete aspects such as crack propagation, shear, and anchorage of the reinforcing bar can be related to split tensile strength. The indirect tensile strength was evaluated at 56 days. All mixes with

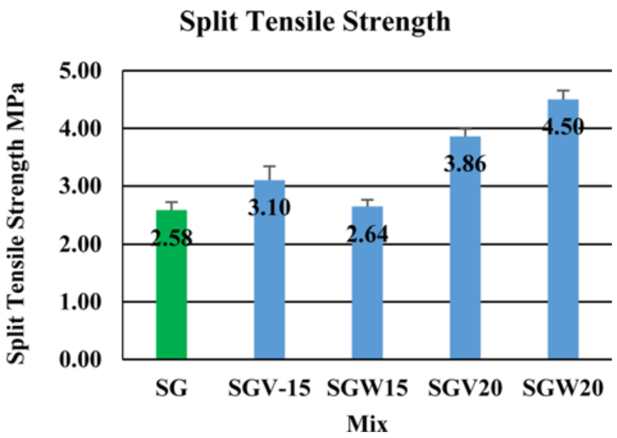

Fig. 8. Split Tensile Strength 56 Days

CPWs showed higher split tensile strength in comparison to the base mix (Fig. 8). The 56 days' indirect tensile strength of the SGV20 and SGW20 mix was increased by 49.62% and 74.54%, respectively. However, the trend of compressive strength is different because of the polymerization process at ambient curing, the low reactivity of CPWs, and the uniformity of CPW. Also, the tensile strength of GPC depends on the bond between geopolymer gel and aggregates. The increase of angular shape CPWs and GGBS particles in the matrix increased the integrity of aluminosilicate gel (Fig. 2). The interlocking of gel particles formed due to CPW and GGBS increased the bond of the geopolymer paste and created compact paste (Fig. 18). In addition, the amorphous silica in CPWs boosted tensile strength. In contrast, Huseien et al. (2018) reported a reduction in the split tensile strength of alkali-activated mortar when GGBS was partly exchanged by C-W-P. The reduction in tensile strength was attributed to a decrease in CaO content as CPW replaces GGBS slowing chemical reactions to produce C-A-S-H gel (Huseien et al., 2020). In the present study, GGBS content is constant. This specifies that replacing fly ash by CPW is better than replacing GGBS by CPW considering the strength criteria.

Figure 9 compares the tensile strength with previous findings and obtained values as per international standards. The results are presented to compare the data with past studies and not to predict any relationships. It shows experimental results, which

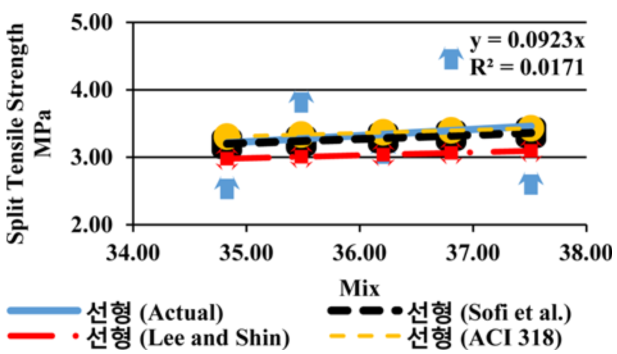

Fig. 9. Split Tensile Strength vs. Compressive Strength

match with those predicted by ACI 318-19 (2019); Lee and Shin (2019); Sofi et al. (2007). The relation was established with 5 sample data for very short-range compressive strength (Fig. 9). However, the fact that the R^2 value approaches zero indicates more variation in the linear relationship between compressive and split tensile strengths. This is because of the difference between the compressive and split tensile strength results. This variation was caused by the slow polymerization process attributed to ambient curing and different binder compositions.

3.4 Modulus of Elasticity (MOE) of GPC

MOE of concrete depends on compressive strength. It is a significant property for the design of structural concrete. A high value of MOE offers greater resistance to stresses. Fig. 10 depicts the results of MOE at 56 days. All mixes with CPWs replacement showed improved MOE compared to the base mix. The MOE was increased by 5.6%, 5.1%, 2.9%, and 5.6% for mix SGV15, SGW15, SGV20, and SGW20, when compared with SG. Fig. 11 compares experimental MOE values with IS 456 (2000) and earlier research findings (Diaz-Loya et al., 2011; Nath and Sarker, 2017). The relationship is obtained using 5 sample data. The R^2 value obtained through the relation is 0.5. MOE results of the study are 16 to 23% lower than projected by Nath and Sarker (2017). The curing temperature in both studies was similar, but the difference in the mix proportions caused a variation. Similarly, the study's MOE results are lower than those from IS 456 (2000) for standard concrete. The experimental results are almost half than suggested

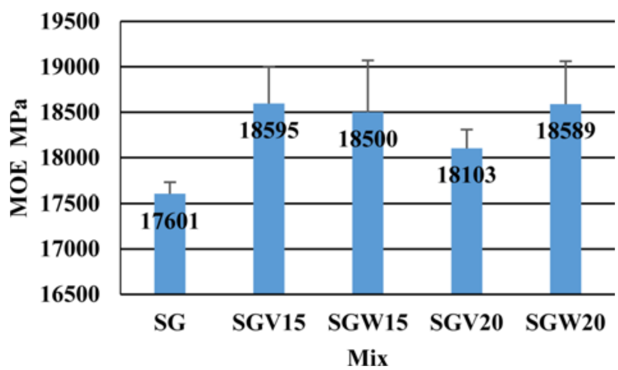

Fig. 10. Modulus of Elasticity

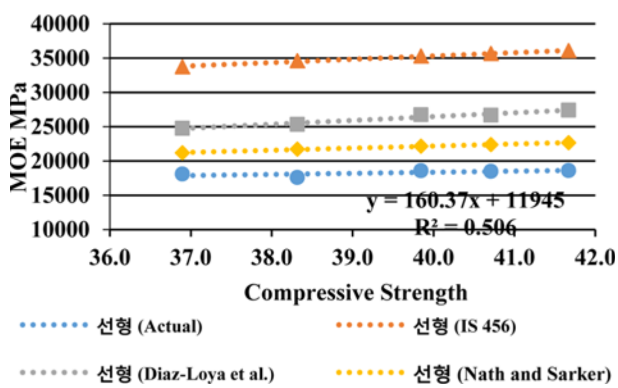

Fig. 11. MOE vs. Compressive Strength

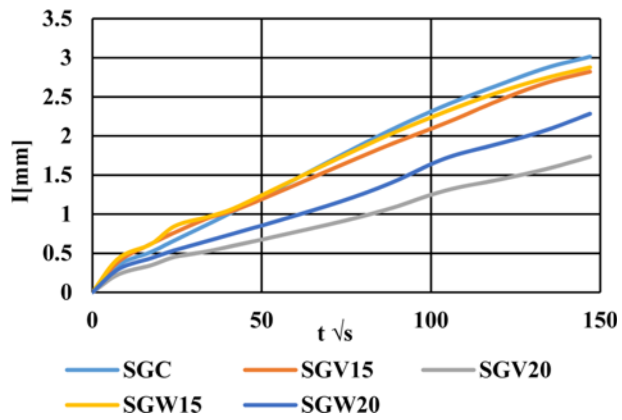

Fig. 12. Sorptivity Test Results

in IS 456 (2000). Likewise, the MOE results are 2/3 times lower than those predicted by Diaz-Loya et al. (2011). The authors used extended oven curing, whereas ambient curing was adopted in the study. It suggests that extended oven curing helps in improving MOE.

3.5 Sorptivity of GPC

Sorptivity is a vital durability parameter for GPC. It specifies the pore structure, permeability, and capillary network of concrete. Generally, the sorptivity of concrete is inversely proportional to concrete compressive strength. However, an independent durability parameter mainly depends on the connectivity of pores in the concrete. Lower sorptivity offers greater resistance against harmful liquids.

Figure 12 presents the sorptivity results obtained for 6 hours duration. The sorptivity was reduced when CPWs were increased. Both WCPW and VCPW improved the pore structure and reduced capillary water absorption. VCPW and WCPW reduced sorptivity by 46.34% and 28.29% for mix SGV20 and SGW20. Here the tests were conducted at 56 days and CPW reactivity is low for ambient curing, it is difficult to discern a consistent pattern between VCPW and WCPW across all sets of tests. Many times, CPW particles do not react and simply serve as filler. The lower sorptivity indicates the reduction in permeability and improved pore structure. Prior studies have shown that CPW can be combined to make a geopolymer paste that is more compact (Sarkar and Dana, 2021). Aly et al. (2018) found that using a 100% CPW mixture resulted in lower sorptivity for geopolymer mortar samples than using a 60% CPW and 40% GGBS mixture. The concrete-based studies showed that the replacement of cement by 10 – 20% CPW reduces sorptivity and permeability (Chen et al., 2022). The permeability resistance of cement-based concrete was improved by 30% CPW in place of fly ash (Cheng et al., 2015).

3.6 Acid Resistance of GPC

The resistance of GPC against sulfuric acid (H_2SO_4) was investigated by immersing concrete specimens in a 5% H_2SO_4 acid solution in water. The specimens were prepared and preserved

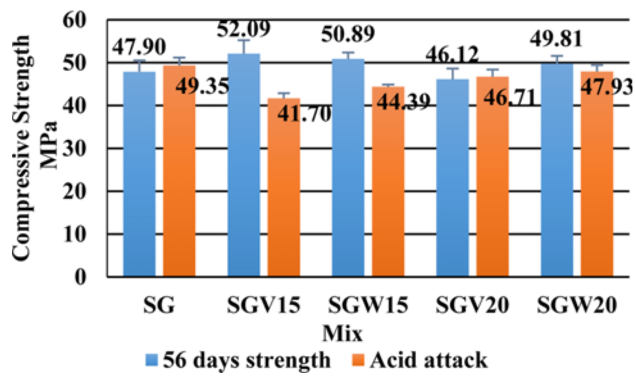

Fig. 13. Compressive Strength and Acid Immersion Strength

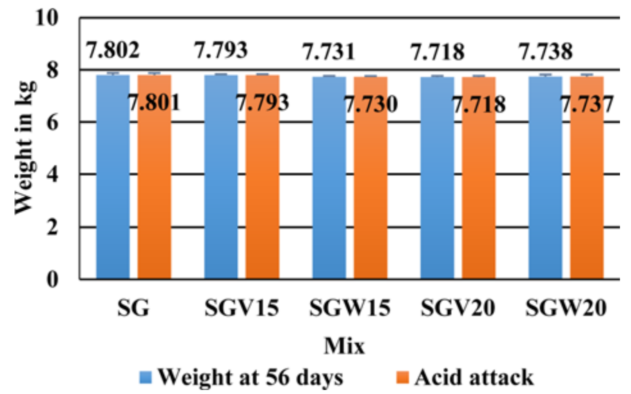

Fig. 14. Weight Loss after Acid Immersion

in ambient condition for 56 days. After 56 days the specimens were immersed in a sulfuric acid water solution for 28 days. The difference in compressive strength (Fig. 13) and weight loss were measured (Fig. 14). Weight loss was found negligible for all mixes. The strength of the SG mix improved by 3% after the acid immersion test. Yang et al. (2021) reported that "the compressive strength of fly ash-based GPC after acid immersion of 28 d increased to some extent due to the presence of gypsum".

In comparison to the SG mix, the compressive strength decreased by 20%, 8%, 2.5%, and 3.7% for SGV15, SGW15, SGV20, and SGW20 respectively. At the same time, loss of strength was reduced for SGV20 and SGW20 compared to SGV15 and SGW15. This revealed the improvement in micropores obtained in sorptivity results. It suggests enhancement in microstructure when 20% fly ash is substituted by CPWs. Furthermore, the loss in strength except SGV15 is higher than the target strength. It implies the better performance of multi-binder GPC against sulfuric acid attacks. The reduction of fly ash content by partial substitution of CPWs moderately affected the acid resistance of GPC. The partial replacement of GGBS by C-W-P decreased strength loss after acid immersion (Huseien et al., 2020). Shah and Huseien (2020) reported that 70% C-W-P, 20% GGBS, and 10% of fly ash gave minimum loss in bond strength after acid immersion. This suggests that lowering GGBS levels while boosting fly ash and CPWs improve strength loss against acid attack. The residual strength of fly ash GPC was high compared

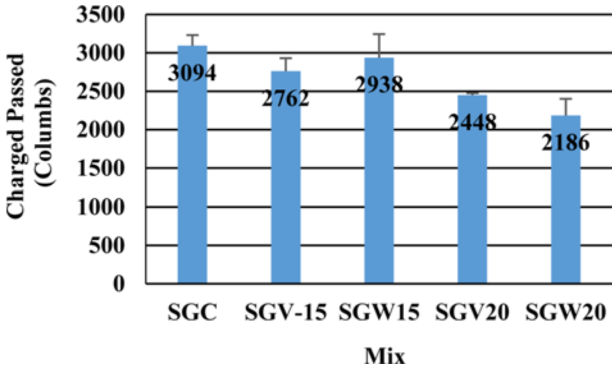

Fig. 15. Rapid Chloride Penetration Test Results

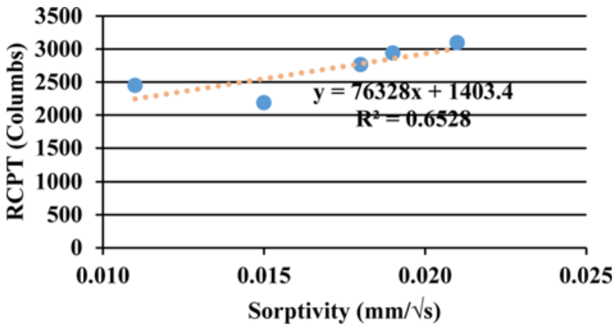

Fig. 16. Relation of RCPT and Sorptivity

to Matakaolin based GPC at 98 d (Yang et al., 2021). Mehta and Siddique (2017) reported deterioration of fly ash GPC for 30% OPC replacement because of additional calcium sulfate products in the mixture. This further confirm that increasing GGBS or calcium based binder may reduce the acid resistance of the GPC.

3.7 Chloride Resistance of GPC

The ingress of chloride is an important parameter for long-term concrete durability. The low chloride permeability increases the resistance against corrosion. The rapid chloride permeability test (RCPT) is a widely accepted test to measure the chloride penetration of concrete. The results of the study gave moderate chloride permeability. Despite this, a rise in CPWs reduced the total charge passed over the course of six hours. The maximum reduction was seen in SGW20 and SGV20 (Fig. 15). The chloride penetration results also confirm the sorptivity results. The CPWs densify the concrete microstructure and reduce the capillary pores (Fig. 18) (Chen et al., 2022). The relation between the sorptivity test and the RCPT test was established based on experimental results (Fig. 16). The past research on cement-based SCC reported a reduction in total charge passed as CPW content was increased. The authors also reported a lower charge passed for CPW replacement with cement than GGBS replacement with cement (Ali et al., 2016). The cement-based mortar also showed improved chloride resistance when cement was replaced by 20% ceramic polishing residue (Li et al., 2020).

3.8 Water Absorption of GPC

Figure 17 illustrates GPC water absorption in cold and boiling

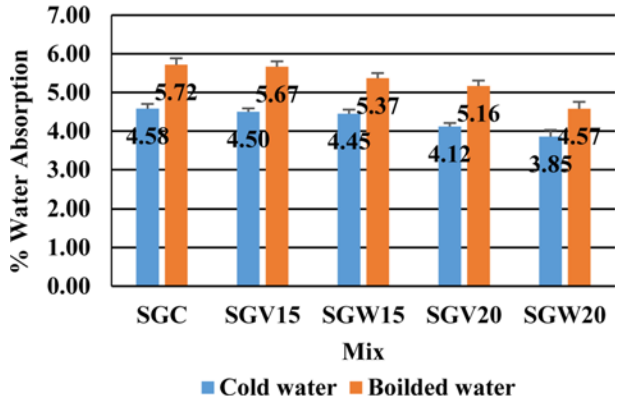

Fig. 17. Water Absorption of GPC

water. The lower water absorption indicates low porosity and dense concrete. As CPW increased, the percentage of water absorption decreased. For all mixes, cold water absorption was less than 5% and boiling water absorption was less than 6%. The results match the sorptivity results, which show that the replacement of VCPW and WCPW improved the durability of GPC. A water absorption rate of less than 3% is ideal, 3 – 5% is adequate, and 5 – 7% is poor (Jindal et al., 2020). A past study reported that replacing GGBS with 5 to 50% CPW reduces water absorption (Rashad and Essa, 2020). The ambient curing benefits in reducing the porosity and helped in the polymerization process. At the same time, temperature curing can increase the porosity of the concrete due to the loss of water (Kaya, 2022).

3.9 SEM Analysis

The fragmented concrete sample was used to capture SEM images of GPC. The samples were coated with platinum prior to image capture. In Fig. 18, the SEM pictures of SG, SGV15, SGW15, SGV20, and SGW20 were shown.

The microstructure of the geopolymer consists of unreacted particles, partially reacted fly ash, GGBS, and CPW particles. It also shows the cracks, voids, and geopolymer gel (Fig. 18). Fig. 18(a) shows large voids with unreacted fly ash particles, and partially reacted slag diluted in geopolymer gel. Fig. 18(b) demonstrates a decrease in unreacted fly ash particles and an increase in unreacted CPW particles. In addition, it contains dense geopolymer gel, partially reacted slag, and reacted CPW than the image of SG mix. Similar points are also observed in Fig. 18(c). Figs. 18(b) and 18(c) revealed that the reacted GGBS and CPW particles have a better bonding.

As VCPW and WCPW concentrations increased in the matrix, a more compact and dense gel was obtained (Figs. 18(d) and 18(e)). A previous study found that combining CPW and GGBS resulted in a compact geopolymer paste (Rashad and Essa, 2020; Zhang et al., 2021). The unreacted CPW also contributes to the formation of a dense microstructure through the filler effect (Sarkar and Dana, 2021). The SEM images, sorptivity, water absorption, and RCPT results revealed that using CPW improved the impermeability of concrete.

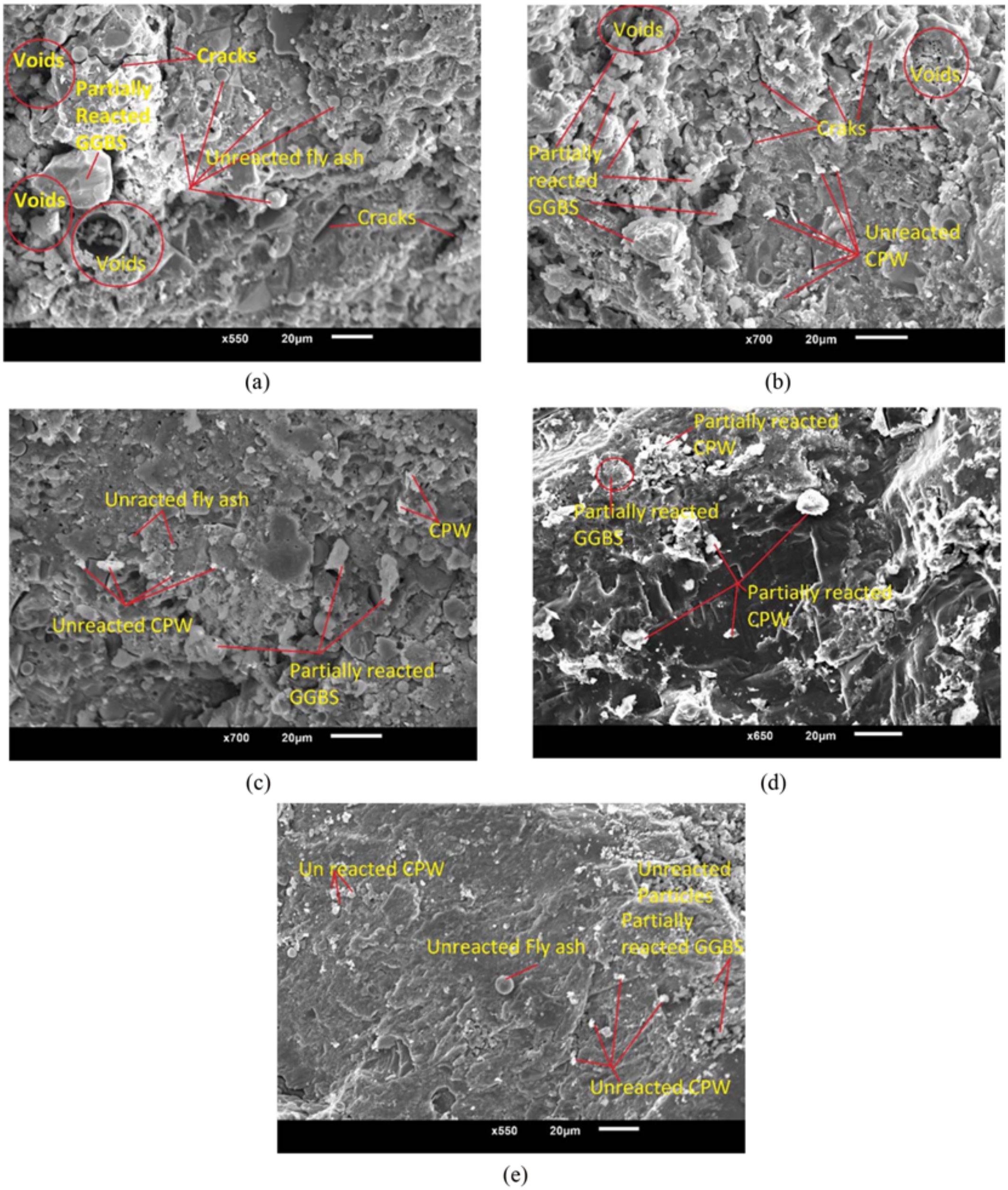

Fig. 18. SEM Image of: (a) SGC, (b) SGV15, (c) SGW15, (d) SGV20, (e) SGW20

Table 6. CO_2 Emission Factor for GPC Ingradients

Material	Emission (kg CO_2-e/kg)	Source
OPC	0.895	(Meshram and Kumar, 2021)
Fly ash	0.063	
GGBS	0.037	
Na_2SiO_3	0.697	
NaOH	1.390	
CPW	0.008	Calculated
CA	0.005	(Mithun and Narasimhan, 2016)
FA	0.005	
Admixture (A)	0.60	

3.10 Carbon Footprint

The carbon emissions (CE) of the multi-binder GPC were evaluated. The analysis aims to know the effect of CPW on CE. The carbon emission factors (E_c) of the GPC ingredients were taken from past research (Table 6). The E_c for CPW has been calculated using the energy consumed in drying and crushing the waste. The data used for the calculation of E_c for CPW are presented in Table 7. The CE calculated here is for the ingredients used for the production of concrete only; the CE for mixing, transporting, and placing of concrete is not considered.

The CE of GPC was governed by alkaline activators (Fig. 19). More than 50% CE was produced due to Na_2SiO_3 and 18% by NaOH. The CE per kg/m^3 of GPC production was calculated for

Table 7. Data for CO_2 Calculation of CPW

Items	Power (Watt)	Capacity m^3	Litre	Ton
Oven drying	1,200	0.18	-	-
Crushing Waste	435	0.08	-	-
Truck Transport	-	12	-	-
Consumption of diesel for 100 km	-	-	9	-
CO_2 emission for 1 litre diesel	-	-	-	0.0027
CO_2 emission for 1 kwh electricity	-	-	-	0.00013

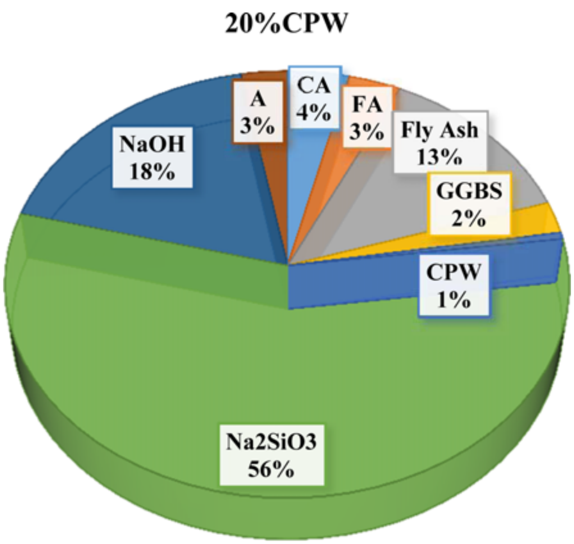

Fig. 19. Distribution of CO_2 Emission for GPC

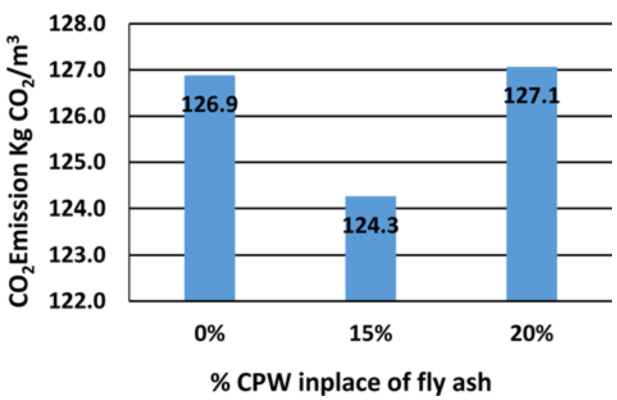

Fig. 20. CO_2 Emission of GPC

multi-binder GPC mixes (Fig. 20). This further validates the results of Salas et al. (2018) who reported 55% contribution of Na_2SiO_3 and 10% of NaOH for the production of GPC block. However, they used heat curing and the contribution of heat curing was found 17% which is zero in the present study. As concrete produced at ambient temperature in the study it reduced approximately 40 kg-CO_2/m^3 compared to oven-cured GPC (Turner and Collins, 2013).

The replacement of fly ash with 15% CPW reduced the CE by 2.6 kg CO_2-e/m^3. The replacement of fly ash with 20% CPW increased the CE by 0.2 kg CO_2-e/m^3. The use of chemical admixture for SGV20 and SGW20 increased CE. The CE for similar grades of cement and slag-based concrete was found 289 kg-CO_2-e/m^3 which is very high compared to the developed GPC at ambient temperature.

4. Conclusions

1. The multi-binder GPC, consisting of fly ash, GGBS, and CPWs, was cured at room temperature. The study found that Fly ash, GGBS, and CPWs can all be added to produce sustainable geopolymer. Fly ash makes the GPC easier to flow, GGBS makes it react fast, and CPW makes it compact.
2. The compressive strength of all mixes with CPWs was improved at 28 days. It was discovered that 56 days' compressive strength was improved for 15% and 20% of WCPW and 15% VCWP as fly ash replacement. The strength of 20% VCPW was reduced marginally at 56 days but it retained target strength for designed M35 grade concrete.
3. The spit tensile strength of GPC was increased when fly ash and slag were combined with CPWs. The split tensile strength for mixes of SGV20 and SGW20 was improved by 49% and 74% when fly ash was replaced by 20% VCPW & WCWP respectively.
4. The MOE of GPC was improved when fly ash was replaced by 15 to 20% CPWs. The improvement was noticed near 5%, for 15% VCPW & WCPW. It was improved by 3% and 5%, for 20% VCPW & WCPW respectively.
5. The use of fly ash in multi-binder GPC improves both its workability and its resilience to acid attacks. The acid resistance has decreased as a result of the decreased amount of fly ash brought about by the replacement of CPWs. Despite this, the residual strength of the mixes with CPWs was within the limit that was intended for M35-grade concrete. The maximum reduction was noted as 20% for the mix with 15% VCPW.
6. The sorptivity and water absorption results revealed that the increase of CPWs by 20% significantly reduces the permeability and porosity of GPC. The maximum reduction was noticed for SGV20 and SGW20.
7. The chloride resistance of the multi-binder GPC was increased due to the replacement of fly ash by 20% VCPW & WCPW. SGV20 and SGW20 showed 21 and 29 percent reductions in total charge passed, respectively.
8. The compact and dense microstructure with an increase in CPWs was confirmed by the SEM investigation. The SEM analysis validates the improved microstructure obtained through sorptivity, water absorption, and chloride penetration tests.
9. Fly ash substituted by 15% of CPWs reduced the carbon footprint by 2.6 kg CO_2-e/m^3, but 20% of CPWs increased it by 0.29 kg CO_2-e/m^3.

Acknowledgments

The author(s) may wish to express his or her appreciation for the financial and technical support provided by Charotar University of Science and Technology for this work.

ORCID

Jay Bhavsar https://orcid.org/0000-0002-0342-5173
Vijay R. Panchal https://orcid.org/0000-0002-9050-2359

References

Abdollahnejad Z, Luukkonen T, Mastali M, Kinnunen P, Illikainen M (2019) Development of one-part alkali-activated ceramic/slag binders containing recycled ceramic aggregates. *Journal of Materials in Civil Engineering* 31(2):04018386, DOI: 10.1061/(asce)mt.1943-5533.0002608

ACI 318-19 (2019) Building Code Requirements for Structural Concrete

Ali ST, EL-Dieb AS, Aboubakr SH, Reda Taha MM (2016) Utilization of ceramic waste powder in self-compacting concrete. Proceeding of Fourth International Conference on Sustainable Construction Materials and Technologies, August 7-11, Las Vegas, USA, DOI: 10.18552/2016/scmt4s116

Aly ST, Kanaan DM, El-Dieb AS, Abu-Eishah SI (2018) Properties of Ceramic Waste Powder-Based Geopolymer Concrete. *International Congress on Polymers in Concrete (ICPIC 2018)* 429-435, DOI: 10.1007/978-3-319-78175-4_54

Aly ST, Kannan DM, El-Dieb AS, Taha MM, Abu-Eishah SI (2017) Ceramic waste powder: An alternative ingredient for green concrete. Proceedings of International Structural Engineering and Construction, July 24-29, Valencia, Spain, DOI: 10.14455/ISEC.res.2017.209

Ameri F, Shoaei P, Zareei SA, Behforouz B (2019) Geopolymers vs. alkali-activated materials (AAMs): A comparative study on durability, microstructure, and resistance to elevated temperatures of lightweight mortars. *Construction and Building Materials* 222:49-63, DOI: 10.1016/j.conbuildmat.2019.06.079

Amin SK, El–Sherbiny SA, El–Magd AAMA, Belal A, Abadir MF (2017) Fabrication of geopolymer bricks using ceramic dust waste. *Construction and Building Materials* 157:610-620, DOI: 10.1016/j.conbuildmat.2017.09.052

ASTM 1585-13 (2013) Standard test method for measurement of rate of absorption of water by hydraulic cement concrete

ASTM C1202-19 (2019) Standard test method for electrical indication of concrete's ability to resist chloride ion penetration

ASTM C204-11 (2011) Standard test methods for fineness of hydraulic cement by air-permeability apparatus

ASTM C642-13 (2013) Standard test method for density, absorption, and voids in hardened concrete

Chen X, Zhang D, Cheng S, Xu X, Zhao C, Wang X, Wu Q, Bai X (2022) Sustainable reuse of ceramic waste powder as a supplementary cementitious material in recycled aggregate concrete: Mechanical properties, durability and microstructure assessment. *Journal of Building Engineering* 52:104418, DOI: 10.1016/j.jobe.2022.104418

Cheng Y, Huang F, Liu R, Hou J, Li G (2015) Test research on effects of waste ceramic polishing powder on the permeability resistance of concrete. *Materials and Structures* 49(3):729-738, DOI: 10.1617/s11527-015-0533-6

Chindaprasirt P, Rattanasak U (2017) Characterization of the high-calcium fly ash geopolymer mortar with hot-weather curing systems for sustainable application. *Advanced Powder Technology* 28(9):2317-2324, DOI: 10.1016/j.apt.2017.06.013

Davidovits J (1993) Geopolymer cements to minimize carbon dioxide greenhouse warming. *Ceramic Transactions* 37(1):165-182

Davidovits J (2018) Why alkali-activated materials (AAM) are not geopolymers. Publication Technical Paper 25

Diaz-Loya EI, Allouche EN, Vaidya S (2011) Mechanical properties of fly-ash-based geopolymer concrete. *ACI Materials Journal* 108(3):300, DOI: 10.14359/51682495

El-Dieb AS, Taha MR, Kanaan D, Aly ST (2018) Ceramic waste powder: From landfill to sustainable concretes. *Proceedings of the Institution of Civil Engineers - Construction Materials* 171(3):109-116, DOI: 10.1680/jcoma.17.00019

Huseien GF, Ismail M, Tahir M, Mirza J, Hussein A, Khalid NH, Sarbini NN (2018) Performance of sustainable alkali activated mortars containing solid waste ceramic powder. *Chemical Engineering Transactions* 63:673-678, DOI: 10.3303/CET1863113

Huseien GF, Sam ARM, Shah KW, Mirza J (2020) Effects of ceramic tile powder waste on properties of self-compacted alkali-activated concrete. *Construction and Building Materials* 236:117574, DOI: 10.1016/j.conbuildmat.2019.117574

Huseien GF, Sam ARM, Shah KW, Mirza J, Tahir MM (2019) Evaluation of alkali-activated mortars containing high volume waste ceramic powder and fly ash replacing GBFS. *Construction and Building Materials* 210:78-92, DOI: 10.1016/j.conbuildmat.2019.03.194

IS 383 (2016) Indian standard specification for coarse and fine aggregates from natural sources for concrete bureau of Indian standards

IS 456 (2000) Indian standard plain and reinforced concrete code practice bureau of Indian standards

IS 516 (Part 1/Sec 1) (2021) Testing of strength of hardened concrete section 1 compressive, flexural and split tensile strength bureau of Indian standards

IS 516 (Part 8/Sec 1) (2020) Determination of modulus of elasticity section 1 static modulus of elasticity and poisson's ratio in compression bureau of Indian standards

IS 1199 (2018) Indian standard fresh concrete - methods of sampling, testing and analysis. Part 2 Determination of Consistency of Fresh Concrete Bureau of Indian Standards

IS 10262 (2019) Concrete mix proportioning — Guidelines bureau of Indian Standards

Jindal BB, Jangra P, Garg A (2020) Effects of ultra-fine slag as mineral admixture on the compressive strength, water absorption and permeability of rice husk ash based geopolymer concrete. *Materials Today: Proceedings* 32:871-877, DOI: 10.1016/j.matpr.2020.04.219

Kaya M (2021) The effect of micro-SiO_2 and micro-Al_2O_3 additive on the strength properties of ceramic powder-based geopolymer pastes. *Journal of Material Cycles and Waste Management* 24(1):333-350, DOI: 10.1007/s10163-021-01323-3

Kaya M (2022) Mechanical properties of ceramic powder based geopolymer mortars. *Magazine of Civil Engineering* 112(4):11207, DOI: 10.34910/MCE.112.7

Khale D, Chaudhary R (2007) Mechanism of geopolymerization and factors influencing its development: A review. *Journal of Materials Science* 42(3):729-746, DOI: 10.1007/s10853-006-0401-4

Kumar VS, Ganesan N, Indira PV (2017) Effect of molarity of sodium hydroxide and curing method on the compressive strength of ternary blend geopolymer concrete. *IOP Conference Series: Earth and Environmental Science* 80(1):2011, DOI: 10.1088/1755-1315/80/1/012011

Lee S, Shin S, (2019) Prediction on compressive and split tensile strengths of GGBFS/FA based GPC. *Materials* 12(24):4198, DOI: 10.3390/

ma12244198

Li LG, Zhuo ZY, Kwan AKH, Zhang TS, Lu DG (2020) Cementing efficiency factors of ceramic polishing residue in compressive strength and chloride resistance of mortar. *Powder Technology* 367:163-171, DOI: 10.1016/j.powtec.2020.03.050

Lloyd N, Rangan V (2010) Geopolymer concrete with fly ash Proceedings of the Second International Conference on Sustainable Construction Materials and Technologies 3:1493-1504, Ancona, Italy: UWM Center for By-Products Utilization

Mehta A, Siddique R (2017) Sulfuric acid resistance of fly ash based geopolymer concrete. *Construction and Building Materials* 146:136-143, DOI: 10.1016/j.conbuildmat.2017.04.077

Meshram RB, Kumar S (2021) Comparative life cycle assessment (LCA) of geopolymer cement manufacturing with Portland cement in Indian context. *International Journal of Environmental Science and Technology* 19(6):4791-4802, DOI: 10.1007/s13762-021-03336-9

Mithun BM, Narasimhan MC (2016) Performance of alkali activated slag concrete mixes incorporating copper slag as fine aggregate. *Journal of Cleaner Production* 112:837-844, DOI: 10.1016/j.jclepro.2015.06.026

Nath P, Sarker PK (2014) Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition. *Construction and Building Materials* 66:163-171, DOI: 10.1016/j.conbuildmat.2014.05.080

Nath P, Sarker PK (2017) Flexural strength and elastic modulus of ambient-cured blended low-calcium fly ash geopolymer concrete. *Construction and Building Materials* 130:22-31, DOI: 10.1016/j.conbuildmat.2016.11.034

Rashad AM, Essa GMF (2020) Effect of ceramic waste powder on alkali-activated slag pastes cured in hot weather after exposure to elevated temperature. *Cement and Concrete Composites* 111:103617, DOI: 10.1016/j.cemconcomp.2020.103617

Salas DA, Ramirez AD, Ulloa N, Baykara H, Boero AJ (2018) Life cycle assessment of geopolymer concrete. *Construction and Building Materials* 190:170-177, DOI: 10.1016/j.conbuildmat.2018.09.123

Sarkar M, Dana K (2021) Partial replacement of metakaolin with red ceramic waste in geopolymer. *Ceramics International* 47(3):3473-3483, DOI: 10.1016/j.ceramint.2020.09.191

Shah KW, Huseien GF (2020) Bond strength performance of ceramic, fly ash and GBFS ternary wastes combined alkali-activated mortars exposed to aggressive environments. *Construction and Building Materials* 251:119088, DOI: 10.1016/j.conbuildmat.2020.119088

Shoaei P, Musaeei HR, Mirlohi F, Narimani zamanabadi S, Ameri F, Bahrami N (2019) Waste ceramic powder-based geopolymer mortars: Effect of curing temperature and alkaline solution-to-binder ratio *Construction and Building Materials* 227:116686, DOI: 10.1016/j.conbuildmat.2019.116686

Sofi M, Van Deventer JSJ, Mendis PA, Lukey GC (2007) Engineering properties of inorganic polymer concretes (IPCs). *Cement and Concrete Research* 37(2):251-257, DOI: 10.1016/j.cemconres.2006.10.008

Turner LK, Collins FG (2013) Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete: *Construction and Building Materials* 43:125-130, DOI: 10.1016/j.conbuildmat.2013.01.023

Yang W, Zhu P, Liu H, Wang X, Ge W, Hua M (2021) Resistance to sulfuric acid corrosion of geopolymer concrete based on different binding materials and alkali concentrations. *Materials* 14(23):7109, DOI: 10.3390/ma142371092

Zhang GY, Bae SC, Lin RS, Wang XY (2021) Effect of waste ceramic powder on the properties of alkali–activated slag and fly ash pastes exposed to high temperature. *Polymers* 13(21):3797, DOI: 10.3390/polym13213797