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STRENGTH PERFORMANCE OF HIGH-STRENGTH GEOPOLYMER CONCRETE INCORPORATING CERAMIC TILE AND CONCRETE WASTE FOR IN-SITU APPLICATIONS

MEHANSKE LASTNOSTI GEOPOLIMERNEGA BETONA Z DODATKOM MLETIH ODPADNIH PLOŠČIC IN BETONSKIH ODPADKOV PRIMERNEGA ZA UPORABO V GRADBENIŠTVU

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This paper explores the possibility of using ceramic tile waste (CETW) and concrete waste (CEW) as feedstocks in the production of alkali-activated geopolymer concrete (GPC) to be used for in-situ structural applications. Binary mixtures of CETW and CEW were made in different ratios (70/30, 60/40, 40/60, 30/70) and contrasted with ternary mixtures that contained other cementitious materials (SCMs) (metakaolin MEK, ground granulated blast furnace slag GGBFS and class F and C fly ash FA) at a 30 replacement. ASTM standards were used to examine the fresh properties, mechanical performance and microstructural behavior. The flowability was 180-210 mm and setting times were 55-180 minutes according to the ratios of SiO_2/Al_2O_3 and Na_2O/SiO_2. The maximum binary strength (48.6 N/mm^2, 28 days old) was attained at 40 percent CETW and 60 percent CEW (SiO_2/Al_2O_3 = 12.3; Na_2O/SiO_2 = 0.18). Ternary 30% GGBFS mixes recorded compressive strength up to 64.4 N/mm^2 at ambient curing, due to increased availability of Ca_2^+ to form CASH/CSH gel. Denser gel networks in optimized mixes were microstructurally analyzed (XRD, SEM-EDS, FTIR). An assessment of sustainability reported 35–45% of the reduction of the embodied CO_2 emissions compared to OPC. These results indicate the viability of CETW and CEW-based geopolymer concrete as a viable alternative in-situ application (pavements, structural walls, and foundations).

Keywords: ceramic tile waste; concrete waste; geopolymer concrete; ground granulated blast-furnace slag; in-situ construction; sustainability

V članku avtorji obravnavajo možnosti uporabe odpadnih keramičnih ploščic (CETW; angl.: ceramic tile waste) in odpadnega betona (CEW; concrete waste) kot vhodnih surovin za proizvodnjo alkalno aktiviranega geopolimernega betona (GPC; angl.: geopolymer concrete), namenjenega neposrednji vgradnji (tlaki, konstrukcijski zidovi in temelji). Pripravili so binarne mešanice CETW in CEW v različnih razmerjih (70/30, 60/40, 40/60, 30/70) in jih primerjali s ternarnimi mešanicami, ki so vsebovale 30 %-tne dodatke različnih materialov (SCM; angl.: cementitious materials): metakaolin (MEK), mleto granulirano plavžno žlindro (GGBFS) in elektrofiltrska pepela (FA) razreda F in C. Za preučevanje lastnosti svežih mešanic, mehanskih lastnosti in mikrostrukturnih značilnosti so uporabili ustrezne ASTM standarde. Razlez mešanic je znašal od 180 do 210 mm, časi vezanja pa od 55 do 180 minut, odvisno od razmerij SiO_2/Al_2O_3 in Na_2O/SiO_2. Največja trdnost binarne mešanice (48,6 N/mm² pri starosti 28 dni) je bila dosežena pri deležu 40 % CETW in 60 % CEW (SiO_2/Al_2O_3 = 12,3; Na_2O/SiO_2 = 0,18). Ternarne mešanice s 30 % GGBFS so pri strjevanju v okoljskih pogojih dosegle tlačno trdnost do 64,4 N/mm², kar je posledica povečane razpoložljivosti ionov Ca^{2+} za tvorbo gela na osnovi kalcij-alumo-silikatnega hidrata in kalcij-silikatnega hidrata (CASH/CSH). Gostejše mreže gelov v optimiziranih mešanicah so avtorji mikrostrukturno okarakterizirali z metodami XRD, SEM-EDS in FTIR. Ocena trajnosti je pokazala zmanjšanje vgrajenih emisij CO_2 za od 35 do 45 % v primerjavi s klasičnim portlandskim cementom (OPC). Rezultati kažejo, da je geopolimerni beton na osnovi CETW in CEW ustrezna alternativa za uporabo pri neposredni vgradnji.

Ključne besede: odpadne keramične ploščice, odpadni beton, geopolimerni beton, mleta granulirana plavžna žlindra, neposredna vgradnja, trajnost

1 INTRODUCTION

Waste produced during construction, demolition and rehabilitation of buildings and infrastructure are known as construction demolition waste, which causes ecological and environmental issues.[1–8] According to reference[2] the concrete and ceramic tile manufacturing sector was responsible for over 10 billion tons worldwide, which accounts for 50 % of the construction waste.[19,3] Due to the indecomposable nature of the materials, it created problems like contamination, land filling and health issues.[9–13] So, to control these problems researchers found an alternative solution of recycling the construction demolition waste[12–18] in various construction applications that form a greener environment.[1,11,12] Reusing CETW and CET in GPC showed a greater impact in reducing the CDW and a greener solution to the sustainable environment. As per[18] GPC mixtures release less CO_2 by up

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to 80 % and absorb less energy than OPC. To effectively manage these wastes and improve the technical and sustainable benefits of geopolymer concrete CDW materials are the best route for a geopolymerization process.[19–24]

Geopolymerization occurs when silico-aluminate-rich materials (Si^{4+} and Al^{3+}) and Ca^{2+} dissolve in alkali hydroxide and silicate solutions. This resulted in the amorphous to semicrystalline formation of aluminosilicate gels with a tetrahedral structure (AlO_4 and SiO_4).[8–10] The primary factors influencing the GPC were the alkaline solutions' concentrations and the precursor. Sodium aluminate silicate hydrate gel was produced when MEK, class F flyash were used in a GPC mix.[23–26] NASH gel is formed as a long linear chain when the high Ca precursors used were GGBFS and class-C FA was used as a long linear chain.[25–30] The present research showed that the use of CEW materials such as ceramic, brick and concrete waste have separate activation processes in the geopolymer systems and the important contents present in the CEW such as silica, alumina, and calcium. Based on the design parameters, the masonry and ceramic geopolymer mix were processed through physical mix design, altering the alkaline solutions, and using different sodium or silica modulus.[17,18] Interesting results were obtained during the temperature maintained between 60–100 °C.[31–33] CETW materials were synthesized with Na_2SiO_3, KOH, and NaOH and cured at 60 °C. It exhibited a compressive strength up to 60 N/mm^2 when they are activated with these three activators. References [34–39] performed the effect of NaOH and Na_2SiO_3 sodium silicate solutions from 8 M to 14 M molarity and the earlier fineness and the compression strength obtained for CETW and masonry waste were hydrated at various temperatures. The result showed a maximum strength of 18 N/mm^2 and 5 N/mm^2 at 60 °C. References [40–45] utilized 100 % CETW and 100% brick waste (BW) and activated with the alkaline solution of NaOH and cured at the temperature of 80 °C. The maximum strength obtained for CETW and BW are 58 N/mm^2 and 40 N/mm^2, respectively. Moreover, some researchers tried to reutilize the CaO-rich CET as an initial material in the GPC mixture. But the optimum result was not obtained at the higher temperature of 70 °C due to the individual use of the concrete waste used higher fineness of concrete waste and temperature at 60-90 °C to obtain a mono geopolymer mixture but attained a reduced compressive strength of 14 N/mm^2 at 90 °C.[34–36]

The utilization of both the CETW and CET in GPC showed an effective strategy to optimize sustainability. The hardened properties of the CET mix were also enhanced. The effects on the replacement of CETW by concrete and calcium-rich concrete to obtain the hardened properties of GPC mixtures.[46–49] The result showed a compressive strength of about 42 N/mm^2 for the mixtures of 90 % CETW and 10 % CET was obtained, which are cured at 90 °C.[50–54]

Research was carried out to find the influence of enhanced CETW and CET compositions. The mixtures were used at 20 % and 60 %. The fresh and hardened properties of the binary composition were identified. The fresh properties such as flow spread diameter and workability were calculated.[55,56] The optimum strength of the binary mixtures along with the ternary compositions are calculated. The ternary compositions include CETW and CET along with supplementary cementitious composites such as MEK, GGBFS, CFA and FFA. The calcium-oxide-rich CEW and GGBS were used in this study as it releases Ca^{2+} ions into the alkaline environment that helps in the formation of calcium aluminosilicate hydrate (CASH) and calcium silicate hydrate (CSH gel). The formation of CASH and CSG gel reacts with the NASH-type geopolymer that in turn increases the early age reaction leading to the matrix densification and mechanical strength of the geopolymer concrete. The balanced use of silica/alumina content enhances the polymerisation effect and the formation of a stable Si-O-Al linkage in the geopolymer concrete. The addition of excess silica reduces the dissolution efficiency and delayed geopolymerization effect and, on the other hand, a reduction in silica content weakens the gel connectivity and reduced the strength development. The curing temperature are maintained at (50, 75 and 100) °C for 24 h to obtain the strength. Microstructural studies were carried out for both the binary and ternary compositions. The other tests such as FTIR, XRD, SEM were carried out.

2 MATERIALS AND METHODOLOGY

2.1 Materials

From the demolished building, concrete waste and ceramic tile waste were collected. The undiluted CETW was made from porcelain wall tile and CET crumbled in a laboratory ball mill and a jaw crusher. Then the materials are sieved to 75 μm to obtain a precursor powder. The other materials such as MEK, GGBFS, class F[4–7] flyash were collected based on ASTM standards. The specific gravities of CETW and CET were 2800 kg/m^3 and 2700 kg/m^3. The specific gravities of MEK, GGBFS, FFA and AFA are calculated as per ASTM standards and were 2400 kg/m^3, 3000 kg/m^3, 2400 kg/m^3, 2200 kg/m^3. The sieve analysis of the CDW and SCMs were (29, 28.5, 10.7, 17, 36.5, 14. 3) μm, respectively. X-ray fluorescence test determined the chemical structure of the materials. XRD analysis showed the crystalline pattern of both CETW and CET powders. CET has a higher crystalline structure than CETW.

The SEM patterns were observed for the CETW and CET powders. The result shows that both are comprised of asymmetric particles in angle formation, but some part of the CET powders viewed round-shaped particles due to the presence of nonreactive cement molecules. The SEM, EDS and XRD interaction images for the samples are as in **Figure 1**. The activator solutions which are

used to activate GPC are NaOH and Na_2SiO_3. The composition of the waste materials used in this research work are tabulated in **Table 1**.

There was a significant difference in the chemical and morphological properties of CETW and CEW. CETW demonstrated a high level of SiO_2 (60.41) and an-

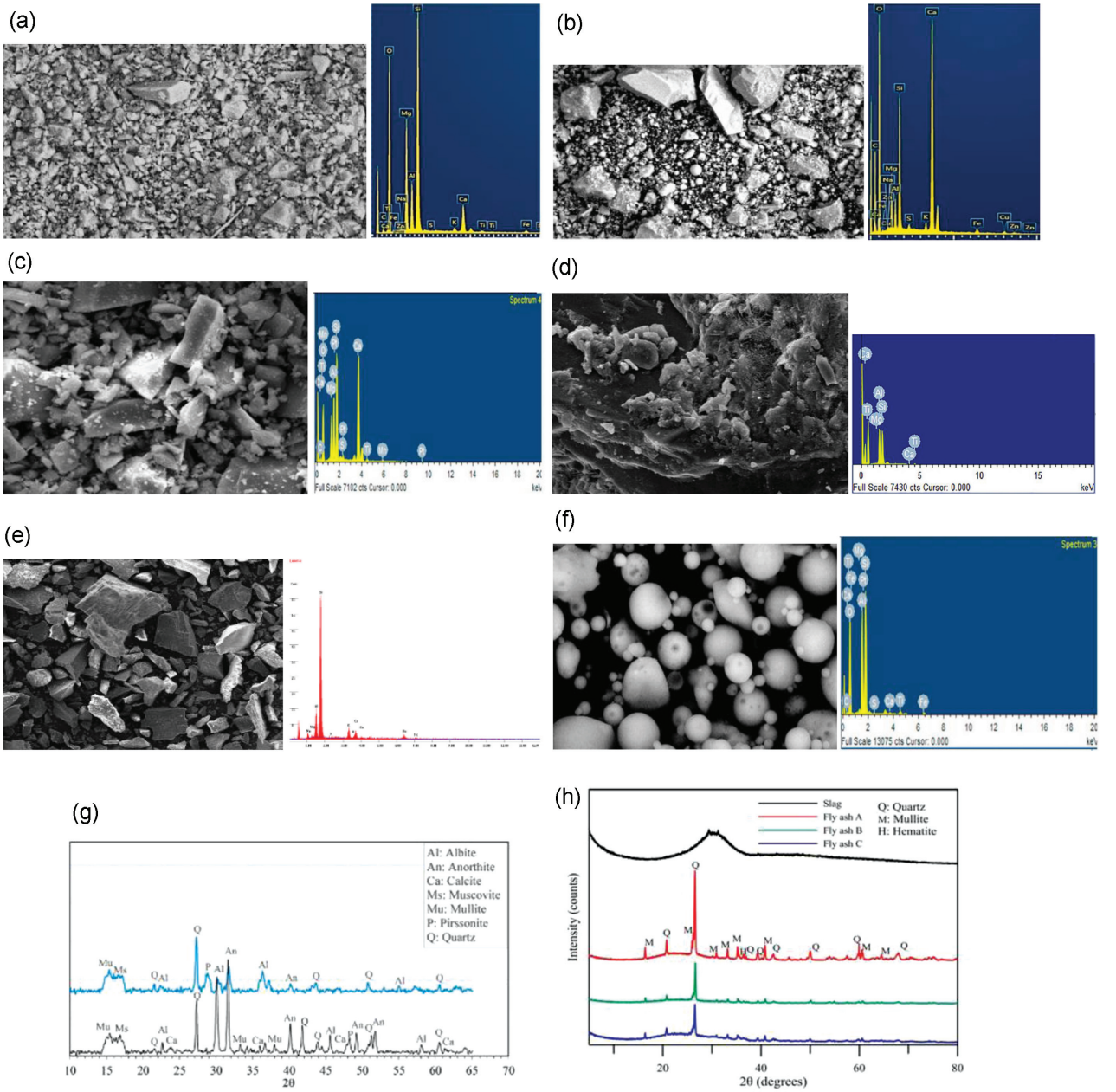

Figure 1: SEM, EDS from a) to f) and XRD analysis of g) CETW, CEW and h) GGBFS, fly ash waste materials: a) CETW, b) CEW, c) GGBFS, d) Metakaolin, e) M Sand, f) Flyash, g) CETW and CEW, h) GGBFS, Fly ash

Table 1: Chemical structure of waste materials

Chemical Composition	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	MnO	Na_2O	K_2O	Specific Gravity
CETW	60.41	9.78	0.98	0.42	5.99	17.42	0.01	0.24	0.71	2.77
CEW	23.21	3.94	1.91	0.19	29.89	8.31	0.075	0.59	0.64	2.69
FFA	54.11	26.59	9.69	0.88	3.61	1.78	0.02	2.42	1.62	2.39
CFA	37.52	20.12	5.71	1.29	20.74	4.67	0.02	4.41	0.61	2.37
GGBFS	36.20	12.70	0.33	0.79	42.24	7.98	0.31	0.15	0.32	2.39
MEK	54.86	37.88	1.78	1.38	0.02	0.17	0.01	0.02	0.24	2.37

Table 2: Geopolymer Binary Mix proportions

Mix proportion	CETW	CEW	Liquid /Solid Ratio	CETW	CEW	NaOH	Na_2SiO_2
GPC7030	70	30	0.3	970	250	367	363
GPC6040	60	40	0.3	740	490	400	324
GPC4060	40	60	0.3	500	755	423	261
GPC3070	30	70	0.3	260	1030	393	260

Table 3: Geopolymer Ternary Mix Proportions

Mix proportion	CETW	CEW	Supplementary Waste Materials (SWM)	CETW	CEW	SWM	NaOH	Na_2SiO_2
GPCMEK30	30	40	30	425	30	180	480	235
GPCGGBFS30	30	40	30	310	576	370	490	222
GPCCFA30	30	40	30	430	40	370	520	181
GPCFFA30	30	40	30	310	560	370	470	235

gularity, and thus increased the water requirement and reduced a working capacity. CEW by comparison included more CaO (29.89) and finer, partially rounded particle, which increased flowability and speed of setting through rapid release of Ca^{2+}. There was also variability in SCMs: GGBFS offered a high CaO content that is conducive to the formation of CASH, and fly ashes had different reactivity among themselves (based on silica/alumina ratios). This variability affected fresh behaviour, setting time and compressive strength development substantially, and, in this respect, mix design optimization plays an important role.

2.2 Mix Design and Mix Compositions

The geopolymer concrete was prepared for two types of mixtures. The first part of mixtures comprised a binary composition such as CETW and CET. The second part of mixtures comprised a ternary composition such as CETW, CET and supplementary waste materials (SWM). The mix proportions of the geopolymer concrete are taken from the mix design. The mix design procedures are calculated based on the standard codes. The CETW and CET[30,50] are used as 70/30 %, 60/40 %, 40/60 % and 30/70 %. XRD analysis of binary powders, the molecular weight of the elements, the molar ratios were calculated. The oxide ratio used for the entire mixture was 0.3. MEK, GGBFS, CFA and FFA were used in the range of 30 %. **Tables 2** and **3** gives the mix proportions of the binary and ternary components in this research work.

CETW is low-Ca silica-alumina and CEW is Ca-rich. In order to formulate reactive gels with ambient curing, mixes were selected through a constrained mixture strategy to explore a viable Ca-Si balance and also minimized the number of trials. The four combinations, 70/30, 60/40, 40/60, and 30/70 (CETW/CEW) -(i) trace a linear increase in available Ca with steps of the order of 10–20 %, (ii) maintain the activator chemistry fixed (Na_2O/SiO_2 = 0.18–0.22; L/S = 0.30) in such a way that effects observed will be those of precursor chemistry, and (iii) target SiO_2/Al The screening of pilots showed that more radical combinations (= 80/20 or = 20/80) resulted in either inefficient flow or quick deposition; hence, were not considered. That the chosen grid guarantees that each waste stream is significantly represented (= 30 % in one mix) aids the sustainability purpose of the study, as well. Ternary mixes (**Tables 2-3**) fix CETW/CEW at the most effective binary level, and add 30 % SCM to investigate the effect of Ca and aluminosilicate availability on Ca and aluminosilicate at the minimum confounding level.

2.3 Mixing, Casting and Curing of Specimens

Alkaline solutions such as NaOH and Na_2SiO_3 were used in this research study. In an empty container, NaOH flakes were immersed in purified water and swirled for 30 min. To remove exothermal heat the solution is kept in an enclosure. Then Na_2SiO_3 solution is mixed with the prepared NaOH solution, after that they are allowed to cool to remove the heat. All the binary and ternary composition of the mixes were prepared. The procedure was started by mixing binary powders at dry state, then the solutions were poured into the mix gradually. After the preparation of the mix, they were poured into the mould of size 150 mm × 150 mm × 150 mm. Then the moulds were kept on a plastic sealed bag for curing in an ambient environment. A few samples were kept for 1 d curing at high temperature. Then the remaining samples were stored for 28 d at room temperature. Specimens were subjected to two curing regimes. Samples were sealed in plastic bags and stored at a laboratory environment of 27 ± 2 °C and 60–70 % relative humidity to simulate practical in-situ curing. Selected mixes were placed in an oven at 50 °C and 100 °C for 24 h immediately after casting, then transferred to ambient conditions until testing.

2.4 Testing Procedures

Various experiments were carried out to determine the fresh and hardened characteristics of the GPC mixtures according to the ASTM standard codes.

- Flow diameter – calculated based on ASTM standard C230.
- Setting time – calculated based on ASTM standard C191.
- Compressive strength – mechanical strength calculated for 7 and 28 days
- Impact of Supplementary cementitious materials at atmospheric curing – MEK, GGBFS, class C and F type FA were used in the ratio of 40 % in CETW and CET geopolymer concrete
- Effect of curing – temperatures at 50 °C, 100 °C were applied for the sample at normal curing.
- Microstructure – XRD, SEM-EDS, FTIR tests were performed for binary and ternary geopolymer concrete.

3. RESULTS AND DISCUSSION

3.1 Fresh Properties

Flow diameters at 180–210 mm crossed binary mixes. Angular morphology decreased workability with higher CETW and increased flow with CEW because of the higher water absorption and spherical particles, respectively. The SEM established disordered CETW faces versus smoother CEW grains, and their contribution to rheology is affirmed. The resulting diversity of precursor morphology thereby had a direct effect on the flowability and setting behaviour of mixes. The initial set time was 31–49 min; the final set time was 55–180 min. A longer CETW set time caused a slower dissolution of aluminosilicates, and a greater CaO content of CEW caused a faster speed in producing a gel.

The flowability of the geopolymer concrete mixture of binary composition was tested and the result showed that all the CETW and CET binders were suitable for in-situ applications, in which the flow diameter ranges between 180 mm and 210 mm, as represented in **Figure 2**. Improved silica /alumina and sodium /silica molar ratios tend to increase the flowability in which L/S were equal for all the CETW and CET compositions. While mixing increased the amount of Na_2O[15–17] along with increased concentrations the OH^- ions were produced, which reduces the friction between the GPC mixtures.[21–25] It helps in breakage of the covalent bond, resulting in the consequent workability. Due to the increase in OH^- ions in the geopolymer mixture the Ph value is higher, and it causes delayed setting. The flowability of the GPC was enhanced from constituents of the precursor powder. An increase in CETW material in geopolymer mix reduces the workability whereas an increase in CET results in increased workability. This is attributed due to the change in the physical and chemical properties of the binary compositions. Due to porous nature the CETW particle it increases the water consumption during mixing. CETW particles irregular shape and large surface area had negatively influenced the flowability of the geopolymer mix. Higher spherical components with enhanced CET content improve the flowability of binary geopolymers and minimize the surface friction.

Beyond porosity and surface area, particle morphology strongly influenced the flowability. CETW particles have sharp angular edges that facilitated the interlocking of particles between the particles, increasing the internal resistance and slowing down diffusion. By contrast, the CEW particles were relatively smoother and even partially rounded, reducing the number of interlocking forces and allowing improved lubrication in the alkaline solution. Greater volumes of the activator liquid were also absorbed on the irregular CETW surfaces, which basically lowered the volume of free paste able to flow. All these effects justify why increased CETW contents reduced flowability, but increased CEW proportions increased it.

The use of more CETW content increases the water absorption due to the effect of porous and angular particles as it increases the voids, which reduces the workability. From the SEM analysis it was proven that lower strength was obtained due to the patrial reacted components or unreacted components of waste materials used in the study indicates the incomplete dissolution of weak

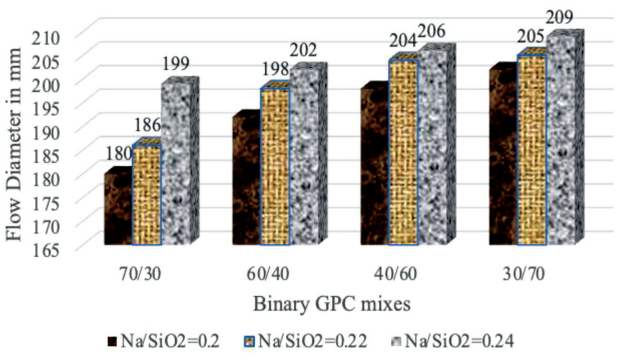

Figure 2: Flow diameter tests for binary GPC mixes (values in mm)

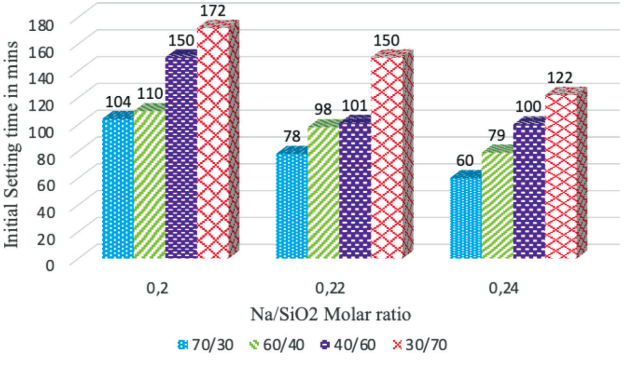

Figure 3: Initial setting time for binary GPC mixes (values in minutes). Error bars represent standard deviation across three specimens.

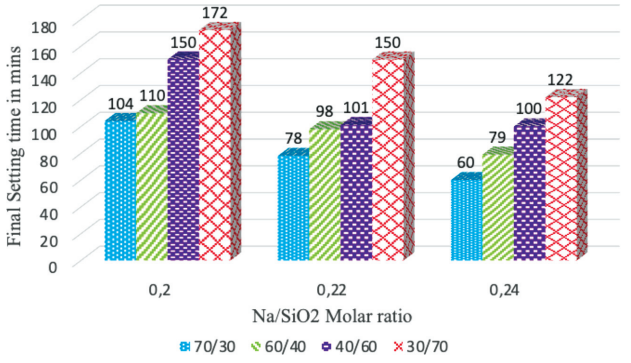

Figure 4: Final setting time for binary GPC mixes

and interfacial bonding. On the other hand, optimised mix shows denser gel matrix with few pores and reduced the unreacted phases thus resulting in superior mechanical performance.

3.2 Setting Time

The setting time of the CETW and CET geopolymer concrete mixes were studied. The initial setting time of the mix were 31 min and 49 min. Ultimate setting time of the GPC mix was between 55 min and 180 min as given in **Figure 3**. Both the setting time were recorded between 60 min and 172 min as in **Figure 4**. The polycondensation stage with the increased heat of hydration have caused due to the improved values of Na/SiO_2. The constituents present in the geopolymer mix enhances the setting time to a greater extent. The setting time extended when CETW content in the mix was increased along with the smaller content of CET material.[17,18] investigated the CETW mortars [51–54] with and without SCMs and concluded that higher concentration of CETW showed extended setting time. According to researchers, the quantity of CaO and increasing CETW content reduces the reaction rate of GPC mixture. The increased CaO content and CET quantities led to faster dissolution of Ca^{2+} ions and better production of calcium aluminate silicate hydrate and calcium silicate hydrate gel.

3.3 Compressive Strength

The compression strength of the binary geopolymer mixes was calculated as per ASTM standards. The compressive strength of the prepared mixes is as represented in **Figure 5** and **Figure 6** for 7 d and 28 d, respectively. The acceptable sodium oxide/silicon dioxide ratio was 0.2 at both ages. Higher ratios of 0.22 and 0.24 resulted in decreased compressive strength. The binary network has resulted in a suitable quantity of silica, Na_2O and (OH) with the equalised design parameters. Improved geopolymerization and gel formation led to increased strength. Improving the high concentration of silica at the target value likely accelerated the development of reaction rates and reduced contact between non-reacted binary particles and sodium silicate and sodium hydroxide solutions, resulting in the formation of lower strength and porous microstructure. Na_2O/SiO_2 molar ratios reached 0.22 and 0.24, increased hydroxyl ion concentration and dissolved aluminosilicates caused earlier development of gel formation. So, this has restricted Ca_{2+} ions movement and dissolution, resulting in lower geopolymerization and mechanical strength. The higher use of Na_2O/SiO_2 led to the increase of OH ions rapidly that resulted on non-uniform suspension of aluminosilicates. This gel formation led to the formation of loosely bound heterogenous reactions instead of well linked geopolymer matrix. Excess alkali distribution of Si-O-Al linkages led to increase pore connectivity that reduces the compressive strength. Microstructural development and cross-linked aluminosilicate networks were altered in binary GPC due to changes in the mix proportions. For optimal Ca^{2+}, Si^{4+} and Al^{3+} ion concentration at 28 d, the binary precursor should be 40 % CETW and 60 % CET. The usage of 60 % CET results in increased strength due to an adequate supply and dispersion of Ca^{2+} ions, which function as polymerisation and balancing agents. The hydrolysis and geopolymerization of calcium aluminate silicate hydrate/sodium aluminate silicate hydrate reactants were accelerated. Sodium aluminate silicate hydrate can be converted to Calcium aluminate silicate hydrate gel by transferring ions if Ca^{2+}

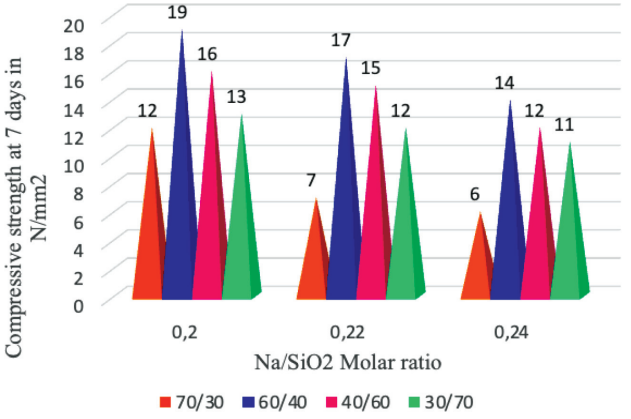

Figure 5: Compressive strength for binary GPC mixes at 7 d

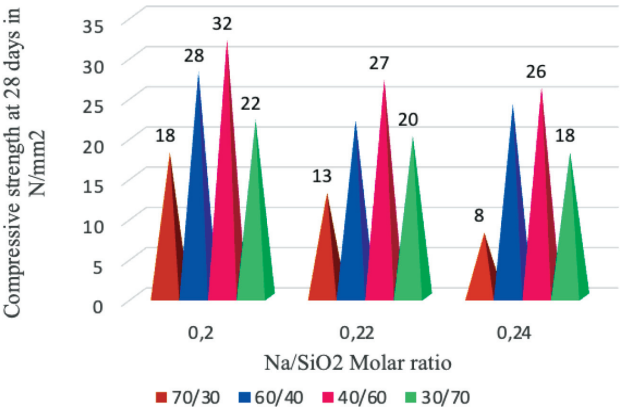

Figure 6: Compressive strength for binary GPC mixes at 28 d

ions move from CET, resulting in indeterminate Calcium aluminate silicate hydrate/ Calcium silicate hydrate products and denser solutions. With 80% CET content, the increased quantity of Ca^{2+} ions may quickly react with $[SiO_2(OH)_2]_2$- to generate Calcium silicate hydrate. Quick production of calcium silicate hydrate gel mostly delays constant processing of the reaction and leads to increased strength. Less than 40 % CETW content in the GPC could be due to low concentrations of alumina and silica and varying chemical reaction rates of precursor powders, leading to weak gel structure and weaker strengths.

The Na_2O/SiO_2 ratio is a critical control parameter in alkali-activated systems: it governs the solution alkalinity, dissolution rate of precursors, and subsequent polycondensation kinetics. In our study an Na_2O/SiO_2 approximately equal to 0.18 produced the best balance between dissolution and controlled polycondensation, yielding a dense and well-crosslinked aluminosilicate/C-S-H matrix and the highest compressive strengths. However, when the Na_2O/SiO_2 ratio was increased to 0.22–0.24, we observed a reduction in compressive strength. Very high OH^- levels accelerate precursor dissolution locally, creating rapid, heterogeneous nucleation and formation of loosely bound reaction products rather than a uniform, well-crosslinked gel. These poorly formed regions become weak points under load. Increasing Na^+ and OH^- raises the ionic strength of the pore solution and perturbs the Al^{3+} charge-balance required for stable Si-O-Al linkages. This reduces the extent of Si-O-Al crosslinking and the degree of polymerisation of the geopolymer gel. Surplus alkali promotes the formation of sodium-rich silicate/carbonate phases and can encourage efflorescence on drying. These phenomena reduce matrix continuity and increase pore connectivity, lowering mechanical properties.

GPCFFA30 still managed to maintain a compressive strength, even if it was lower than that of GGBFS, on ternary blends within the GCCC ternary mix, despite containing reactive aluminosilicates. Several intertwined reasons have been drawn to explain this behaviour. Fly ash class F is known to have a low quantity of CaO in addition to a significant vitreous glass phase, which at moderate temperatures, does not dissolve easily and is highly influenced by the presence of weak alkalis at moderate temperatures. This scenario leads to a deficiency in the timely reserve of Si and Al, which is critical in the rapid formation of Si gel (SiG). This phenomenon diminishes the rate of polycondensation polymer chain formation, FA/SiG. Due to the presence of GGBFS, the soluble Ca ions promote early nucleation and lead to the rapid formation of a C–(A)–S–H/CASH bound structure. This process, together with a CaO dense matrix, leads to superior strength, hence the rationale for the early and late strength. Moreover, the abundance of reactive silica in FA contributes to the excessive consumption of the offered silicates, and hence the formation of a rich silicate quiescent region, which cross-links suppression, activator's concentration and polymer-chain formation. Curing at high temperatures leads to greater reaction rates, and the addition of a small quantity of GGBFS works in increasing the overall compact structure. This set of conditions is considered practical and can be taken for the enhancement of the FA performance.

3.4 Impact of SCMs on Ambient Condition

The mix design of the GPC is indicated in **Table 3**, and the compression strength of the ternary geopolymer mix is represented in **Figure 7**. Binary GPC had the highest compressive strength at a 40-60 proportion at 28 d, which was taken as a sample mixture. Other than GPCFFA30, all SCMs significantly increased the compressive strength of the sample GPC. GPC with 30 % GGBFS produced a higher compression strength of 64.4 N/mm^2 at ambient temperature, indicating a considerable increase of about 32 % compared to the sample ceramic tile waste in the GPC mix. Increased GGBFS content leads to the formation of CASH or CSH in the geopolymeric gel system. GGBFS has provided more Ca^{2+} cations than CET, leading to the formation of new nucleation sites and increased calcium silicate hydrate/calcium aluminate silicate hydrate development. GGBFS's rapid dissolution rate at controlled Silicon dioxide/aluminium oxide and sodium oxide/silicon dioxide ratios probably accelerated polycondensation rates and geopolymerization, resulting in a more compresses GPC matrix and better compressive strength. Incorporating MEK at 28 d resulted in optimal mechanical strength of 44.3 N/mm^2. The ideal proportion of replacement for CETW+ CET+SCM with MEK was 30 %, unlike other mixes where 30 % SCM replacement yielded better results. GPCCFA30 had a lower degree of enhancement, while having a comparable Ca content to GGBFS. Excess silica in the mixture may have delayed or prevented nonreacted particles of class F and class C fly ash, Concrete waste, and ceramic tile waste precursors from dissolving in the alkaline solution. GPCFFA30 may have strengthened silicon-O bonding with Ca-Ca-modified sodium aluminate silicate hydrate gel associated with Calcium aluminate silicate hydrate, resulting in improved compression strengths for binary mixtures. Prolonged curing times using F-Fly ash particles are projected to have a greater benefit due to continued Al and Ca diffusion, which can result in significant Calcium aluminate silicate hydrate gel condensation at elevated stages.

In addition to ambient curing, selected geopolymer concrete mixes were subjected to elevated curing temperatures of 50 °C and 100 °C for 24 h immediately after casting. The results indicated that heat curing significantly accelerated the dissolution of aluminosilicate species, thereby enhancing early-age reaction kinetics. At 7 d, specimens cured at 100 °C displayed up to 25–30 % higher compressive strength compared with ambi-

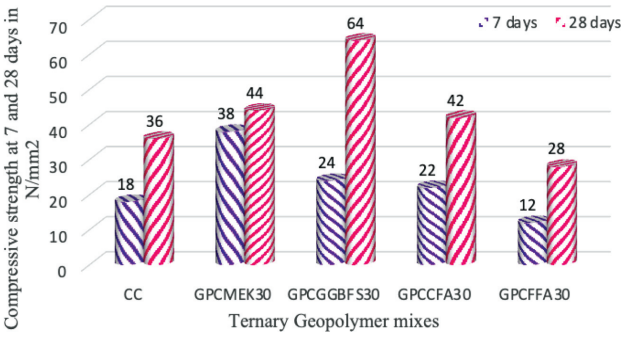

Figure 7: Compressive strength for binary GPC mixes at 28 d

ent-cured samples. This improvement can be attributed to rapid polycondensation and denser calcium–alumino-silicate–hydrate (CASH/CSH) gel formation. However, prolonged exposure to higher temperatures also caused microstructural drawbacks. SEM micrographs revealed increased microcracking in 100 °C-cured specimens, likely due to thermal shrinkage and rapid water loss. XRD patterns confirmed a higher proportion of crystalline phases relative to amorphous gels, indicating less uniform geopolymer networks at 100 °C. Consequently, while early strength improved, long-term mechanical stability and durability may be compromised. At 50 °C curing, a more balanced performance was observed: compressive strength gains of 10–15 % at 28 d compared to ambient curing, along with relatively homogeneous gel structures and fewer cracks than at 100 °C. These findings align with previous studies which reported that moderate thermal curing enhances geopolymerization, whereas excessive heating risks brittleness and microcracking.

3.5 Microstructural Investigation

XRD Analysis

The binary geopolymer concrete XRD spectra are shown in **Figure 1g**. The maximum and minimum strength of binary geopolymer concrete were ratios 40, 60, 70, 30 from the laboratory environment. A semi-crystalline GP with increased peaks of chemical compositions and poor-density transparent phases of pirssonite, calcite, mullite, and muscovite was shown by the spectrum of the provided samples. Binary predecessors showed similar concentrations of crystalline phases, particularly, albite, anorthite and quartz at 31.65°, 30.05° and 27.25° 2θ. Many of these stages were ignored throughout the geopolymer activation, in which it does not contribute to the binary system's strength growth. Producing more amorphous geopolymer gels is linked to the contraction and expansion of the amorphous hook in geopolymer and binary GP, as previously indicated.

The XRD diffractograms were baseline-corrected, and the broad amorphous hump (typical of geopolymer gels) was separated from sharper crystalline peaks. The relative area of this amorphous hump, in relation to the total diffracted intensity, served as a semi-quantitative indicator of the amorphous gel content. Although this methodology fails to yield absolute mass fractions, which would necessitate the incorporation of an internal standard and a complete Rietveld refinement, it allows for a relative comparison across mixes assessed under the same instrument parameters. Optimised ternary mixes (particularly the 30 % GGBFS blend) showed the greatest amorphous hump to crystalline peak intensity ratios and the lowest residual crystalline peak intensities, which suggests that the illy ingredients were dissolved and a gel formed in larger quantities.

SEM and EDAX Results

The results of the binary geopolymer concrete are shown in the Figure 8. Binary geopolymer binders exhibit varied morphological properties, reaction products, and phases depending on chemical characters, design

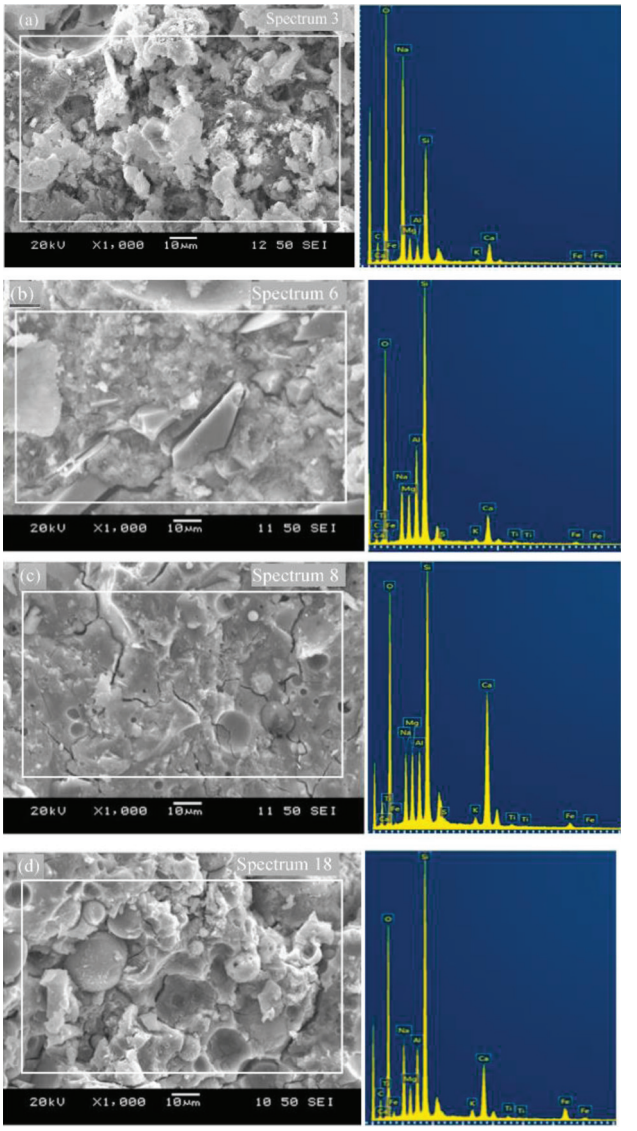

Figure 8: SEM and EDS of a) CETW+CET waste concrete, b) GPCMET30, c) GPCCFA30, d) GPCFFA30

specifications, and curing. Using balanced specifications of silicon dioxide/aluminum oxide and sodium oxide/silicon dioxide with constant and ambient temperature considerably improves dissolution and geopolymer reaction rates. All binary binders including silica, calcium, sodium, and alumina, indicated the same calcium/sodium aluminate silicate hydrate reaction products. SEM images of GPCFFA30 and GPCMEK30 binders are shown in **Figure 8** showing a uneven yet dense micro-structure with several nonreacted/partially reacted particles. In GPCFFA, nonreactive components are mostly FFA, whereas GPCMEK30 shows a combination of CETW, CET, and MEK. This proved the extended processing time of class F fly ash precursor during ambient curing, as described in the paper. The partial replacement of binary GPC with class F fly ash showed more homogeneous and uniform microstructure, with fewer unreacted particles. This indicates that FC has a higher influence in dissolving of CETW and CET precursors than MEK and FF. CEW particles were found to be smoother partially round when compared to the angular CETW particles. This morphology reduced the interlocking, flowability gets improved and increases the disperse on within the geopolymer matrix. Use of finer CEW particles improved the packing density and calcium ion dissolution during geopolymerization.

Sustainability Analysis

The sustainability of binary geopolymer concrete was calculated from embodied CO_2 emission and embodied energy consumption. The CO_2 emissions and energy consumption were computed depending on the energy utilized by a laboratory ball mill and time with capacities of 3.33 kg/h and 4 kg/h for mixing and pulverizing materials. From the literature, **Table 4** shows the CET, CETW, and CO_2 values. The E_e and C_e factors for geopolymers were assessed based on compressive strength and sustainability effect, as specified below:

E_e = embodied energy (MJ/ton) /F_c

C_e = embodied CO_2 (kg CO_2/ton) /F_c

F_c = 28 d compressive strength.

To calculate the overall CO_2 emitted and energy consumed we used the embodied energies and carbon dioxide emissions of each element in the mixture composition. Binary geopolymers had a reduced total energy, E-CO_2, E_f, and C_f factors compared with equivalent strength OPC.

Table 4: Energy and E-CO_2 sustainability analysis

Materials	Energy (MJ/ton)	E-CO_2 (kg CO_2/ton)
CETW	540.	202
CET	810.	303
Na_2SiO_2	1932	545
NaOH	1430	259
CC	5500	1000

4 CONCLUSION

- This study demonstrated the feasibility of producing geopolymer concrete (GPC) using ceramic tile waste (CETW) and concrete waste (CEW) for structural *in-situ* applications.
- The optimized binary mix (40 % CETW + 60 % CEW) achieved a compressive strength of 48.6 N/mm^2 at 28 d under ambient curing, while ternary mixes incorporating 30 % GGBFS reached up to 64.4 N/mm^2. This was due to the correct proportioning of silica/alumina content from CETW for perfect contribution of reactive SiO_2 and Al_2O_3 for geopolymer gel formation and calcium from CEW to activate the Ca^{2+} to accelerate the formation of the CASH/CSH gel. The balanced chemical formation resulted in dense geopolymeric and enriched calcium gel network leading to a higher compressive strength.
- Fresh properties (flow diameter of 180–210 mm and setting times of 55–180 min) confirmed the suitability for on-site placement. Microstructural analyses (XRD, SEM-EDS, FTIR) confirmed dense gel networks, while sustainability assessment indicated a 35–45 % reduction in the embodied CO_2 emissions compared with OPC.
- The practical implication of these results is that dual waste-based geopolymers can be directly applied in field-scale construction such as pavements, foundations, and walls, without the need for elevated curing.
- However, limitations remain regarding the variability of waste composition, processing requirements, and the cost of alkaline activators. Addressing these through optimized material characterization, activator efficiency, and supply-chain integration will be essential for scaling.
- Overall, the study advances the application of geopolymer technology by bridging laboratory research with *in-situ* construction practice, providing both environmental and structural benefits.
- From the previous literatures it was concluded that when the use of CETW and CEW with ternary GGBS blends under ambient curing conditions achieved a strength of 64.4N/mm^2 and binary mixes with 48.6N/mm^2 when compared to the previous studies had a strength range in-between 14–60 N/mm^2. Thus, the novelty of achieving high strength geopolymer concrete with the combination of CETW and CEW at ambient condition was explained clearly.

Limitations

- The chemical composition of CETW and CEW can vary depending on demolition source, which may affect reproducibility of results.
- Large-scale processing (crushing, grinding, sieving) requires additional energy and infrastructure, which may impact cost-effectiveness.

- The cost and environmental footprint of alkaline activators (NaOH, Na_2SiO_3) remain a challenge for widespread adoption.
- Long-term durability aspects (e.g., resistance to carbonation, chloride attack, and freeze–thaw cycles) were not investigated in this study.

Recommendations

- Future studies should focus on field-scale trials of CETW+CEW-based GPC in real *in-situ* environments.
- Optimization of alkaline activator dosage and potential use of alternative eco-friendly activators is recommended to reduce cost and environmental impact.
- Long-term durability tests and lifecycle assessments should be undertaken to establish performance in diverse climates and service conditions.
- Standardization of waste processing methods is necessary to ensure consistency of precursor quality.

Implications

- Demonstrates that dual waste-based geopolymers can achieve strengths >60 N/mm^2 under ambient curing, making them suitable for structural *in-situ* applications such as pavements, walls, and foundations.
- Supports circular economy initiatives by diverting ceramic and concrete waste from landfills into high-value construction materials.
- Offers a low-carbon alternative to OPC, with 35–45 % reduction in embodied CO_2, contributing to sustainable infrastructure development.

Declarations

Ethical approval: This research work was carried out by me and it is not published in any other journals.

Ethical approval: All the authors of this paper have given their consent for the participation

Consent for publication: I the author give my consent for the publication of identifiable details, that can include the photograph and details within the

Author Contribution: Karthiga @ Shenbagam Natarajan, Revathi Krishnaswamy and Kannan Vellaipandian have equally contributed to this work.

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