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Technical Notes

Density, strength, chemical solution resistance and shrinkage of sustainable geopolymer concrete containing PET Waste flakes, PET fiber and polypropylene fiber

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Abstract: To produce a sustainable geopolymer concrete different solid wastes were used and properties of the recycled concrete were investigated. Performance of the produced geopolymer concrete is modified by such additions, as observed by different researchers. In this paper, mechanical properties, shrinkage, and sulphate attack resistance of fly ash-based geopolymer (GPC) containing polyethylene terephthalate (PET) waste aggregate, PET waste fiber, and polypropylene fiber (PPF) were investigated. Results indicated that compressive strength is decreased due to PET aggregate addition to GPC, while there is a strength enhancement by using PET and PP fibers. There is a slight loss in flexural strength when using PET aggregate and strength enhancement associated with using PPF. The existence of PET and PP fibers is helpful to change the sudden collapse of flexural specimen to a gradual failure mode. Due to heat curing, instantaneous drying shrinkage is relatively high and changes little with time except for GPC containing PET aggregate. The geopolymer concrete exhibits good sulphate resistance of GPC, in which maximum compressive strength reduction after 30 days of immersion in H_2SO_4 solution was measured to be 6% and the addition of different PET wastes and PPF have some effect in reducing the strength loss.

Keywords—Drying shrinkage, Geopolymer concrete, PET waste aggregate, PET waste fiber, Polypropylene fiber

1. Introduction

The structural and non-structural conventional concretes depend on the hydraulic Portland cement as a binder, but unfortunately producing cement is related to the carbon dioxide (CO_2) gas emission. For instance, ordinary Portland cement contributes approximately 7 to 8% of CO_2 emissions in the atmosphere and energy consumption over 2.5% (Damtoft et al., 2008, Sivakrishna et al, 2020, Omer and Saeed, 2020). Due to the continuous demand, production of cement is expected to increase (Omer and Saeed, 2020, Amran et al., 2020, Nayana and Kavitha, 2017), and consequently, the CO_2 release to the atmosphere will increase. As an alternative, highly efficient applications of both renewable and nonrenewable resources are required to produce a non-Portland cement based concrete since the world continues to endure a series of environmental degradation (Panda et al., 2017, Shalini et al., 2016, Shaikh, 2016).

Geopolymer concrete (GPC) can serve as a suitable alternative to normal concrete (Amran et al., 2020, Hassan et al., 2020, Ahmed et al., 2021a), mainly because this one depends no on the ordinary Portland cement. On using, the CO_2 emission footprints range between 70 and 90% compared to OPC production (Hassan et al., 2020, Paul et al., 2020, Hassan et al., 2019a, Hassan et al., 2019b), and as consequence the GPC with a low environmental footprint offers significant promises for structural applications in the concrete industry (Rangan, 2014). In general, GPC has mechanical properties similar to or better than or even better most of the time than conventional OPC concrete (Hassan et al., 2020, Rangan, 2014, Wallah and Rangan, 2016). Various experimental tests were conducted to evaluate the use of GPC in structural applications, and one of common feature is that the development of this concrete will be a great help to consume industrial waste materials.

Zannerni and Al-Tamimi (2022) worked on mechanical and microstructural properties of geopolymer concrete mixes with different combinations and percentages of alternative cementitious binders. Fly ash, ground granulated blast furnace slag (GGBS) and silica fume were activated using 10 M NaOH solution. The geopolymer concrete with 100% replacement of cement by GGBS was able to achieve a flexural strength of 6.6 MPa at 28 days without the need for heat curing (Zannerni and Al-Tamimi, 2022).

As compared with the other concretes such as normal, high strength and lightweight concretes, GPC is a relatively new construction material. However, there are numerous applications of this novel concrete worldwide especially in Australia, Malaysia, Germany, and Netherlands. Among them one can mention drainage (sewer) pipes (375-1800 mm dia.), wall panels, railway sleepers (Gourley and Johnson, 2005) and precast box culvert (Siddiqui, 2007, Cheema et al., 2009). Also, GPC found applications in multi-story (precast floor beam-slab element) (Sani and Muhamad, 2020, Bligh and Glasby, 2013), airport pavement (Glasby et al., 2015), light weight pavement and deck (Aldred and Day, 2012). Also, there are several walkways, sewer pipes, railway sleepers, burial crypts (Rangan, 2014), precast tunnel segments (Glasby et al., 2015, Glasby et al., 2013), and protective coating (Zhang et al. 2010, Zhang et al., 2012) made of GPC.

On the other hand, different types of plastics are in use (Mohammed and Faqe Rahim, 2020) and consequently there is a large amount of solid wastes. The plastic waste became a serious source of both land and water pollutions, and recycling became an important global issue. There is a chance to use plastic waste concrete in the form of fiber and aggregate (Mohammed, 2017). There is a relatively large amount of researches conducted on the feasibility of using different forms of plastic waste for OPC based concrete (Ahmed et al., 2021b), but for GPC there is a shortcoming in the knowledge and there is a gap needs to be filled. This study has been arranged to investigate experimentally some important properties of GPC contained PET waste fiber and PET waste aggregate. The properties of GPC of different PET wastes were compared with those of GPC reinforced with the synthetic polypropylene fiber (PPF). The results are also compared with those obtained by some researchers who worked on this important topic of engineering materials.

In the sections to follow, review of literature was made to highlight the results of tests conducted on GPC contained different PET waste aggregates, PET fiber and PPF, to highlight any change take place on the measured properties. Firstly, properties of GPC containing other materials in the form of fiber and aggregate may be different from those of Portland cement concrete. Because there are many source materials to be polymerized by the alkali solutions and there is a need for heat curing in some cases such as in the existence of fly ash (FA) to enhance different properties. Further, the early strength of most GPCs is different from that of conventional concrete. Some investigators have compared properties of GPC with those of companion PC based concrete and conclusions were drawn for the comparison sake.

Akcaozog˘lu and Ulu (2014) have carried out tests to show the effect of PET aggregate on alkali-activated slag and slag/metakaolin blended mortar. Slag aggregate was replaced with the PET waste aggregate by up to 100% (20% increment volume ratio). Fresh and dry densities, ultrasonic wave velocity, compressive and flexural tensile strengths were decreased with increasing PET aggregate in the mixture. The reduction of the unit weights and ultrasonic wave velocity were attributed to the low density of PET aggregate compared to that of unground slag aggregate. The ratios of 28-days compressive strength of mixes with 20,40,60,80, and 100% aggregate replacement with PET aggregate were 58.6%, 49.9%, 32.3%, 24.6% and 18.6%, respectively compared with control concrete. The strength loss was attributed to the poor bond between the plastic aggregate and cement paste. Further, water absorption and porosity were increased depending on the PET aggregate ratio in the mix. Their results show that there is a chance to produce structural lightweight concrete made of alkali-activated slag mixtures containing 60% and 80% waste PET aggregate, based on unit weight and strength properties. Further, compressive strengths of alkali-activated slag/metakaolin blended mixtures were lower than alkali-activated slag mixtures at the same curing condition. Lenin Sundar and Raj (2017) tested GPC containing E-waste taken from loosely discarded, surplus, obsolete, broken, electrical or electronic devices from commercial recyclers. 90% FA and 10% GGBS were used as binder, while the sand was replaced with E-waste at 10, 20 and 30%. 20% replacement with E-Waste attained higher strength than the normal M40 grade GPC, in which compressive strength and split tensile strength with E-waste give 14.75 and 6.5% increases compared to virgin GPC. Manjunatha et al. (2018) used plastic granules (high density polyethylene (HDPE)) in GGBS based GPC as a replacement for fine aggregates. Alkali solution/binder ratio was 0.45. Six mixes were made to compare with the addition of HDPE up to 100% (20% increment). Compressive strength was reduced with increasing sand replacement with the plastic aggregate to smaller than one half on using full sand replacement. As compared with that of compressive strength, splitting tensile strength loss was lower especially at lower sand replacement with plastic aggregate. Ahmad Khan et al. (2019) tested GPC prepared with low calcium FA and 10-20 mm size coarse aggregates replaced with HDPE aggregate at different percentages (0%, 10%, 20% and 30%). A degradation of both compressive and splitting tensile strengths was observed and reached to about one half at 30% plastic aggregate content. They concluded that plastic waste can be used in concrete by 10%. In an experiment, Wongkvanklom et al. (2019) tested FA based GPC contained recycled plastic beads by a ratio 0-100%. Results showed a maximum reduction in dry density, compressive strength, splitting tensile strength, flexural strength by 43%, 85.3%, 69.5% and 83.5% respectively when the sand is fully replaced with plastic aggregate. Also, a continuous reduction of thermal conductivity of GPC with increasing recycled plastic beads in the mix was observed. Further, Lazorenko et al. (2022) investigated properties of coal fly ash-based geopolymer mortars of fine aggregate replaced by 20%, 40%, 60%, 80% and 100% PET granules of 0.315–1.25 mm size. Results show that an increase in the plastic aggregate content leads to a decrease in compressive strength and flexural strength, but indirect tensile strength was slightly increased on using 40% PET aggregate as fine aggregate replacement. Workability of fresh geopolymer mixes was close to that of conventional mortar at this replacement level. The reduction of cracking and more ductile failure modes were observed because of using PET flakes. Full replacement of natural aggregate with PET aggregate was advantageous to reduce concrete weight (up to 15%), water absorption (up to 26%) and thermal insulation properties (up to 59%). More recently, Adeleke et al. (2024) studied the efficacy of polylactic acid-type plastic as a 10 mm natural coarse aggregate replacement at 30 and 70% (by weight) in —ground granulated blast-furnace slag based geopolymer concrete. The geopolymer concrete control used an optimum alkaline activator/precursor ratio (0.5) and sodium silicate to sodium hydroxide volume ratio (1.2/0.8). The results illustrate the there is a chance to use this plastic waste in GPC production added by up to 70% to the mix, despite some negative impacts on GPC performance. There was a compressive strength loss because of replacing natural aggregate with plastic aggregate (PA) by 30% and 70% at ages of 7, 28 and 56 days. Furthermore, Zia Ul Haq et al. (2024) worked on geopolymer bricks contained PET waste and different industrial byproducts (rice husk ash, ground granulated blast furnace slag, red mud, construction, and demolition waste). The PET waste was used as a replacement for fine aggregate filler in the GP brick up to 100%. Workability decrease of 14.75%, compressive strength reduction of up to 75%, dry density reduction, and water absorption increase up to 13.73% with full fine aggregate replacement were observed. Using full sand replacement with plastic waste was resulted in impact resistance improvement, and enhancing both ductility and thermal conductivity by 57%.

With regard to utilizing plastic fiber in GPC, PET fiber has been used by the researchers in two basic forms, hand cut plastic fiber obtained from simple shredding and synthetic PET fiber obtained from rigorous recycling process. Physical properties of synthetic PET fiber of dimension, tensile strength, Young's modulus are nearly similar to that of polypropylene fiber (PPF), but the density of PET fiber is higher (1.3-1.4 compared with 0.9 for PPF) (Bhutta et al., 2019). There is a need for heat curing (at least 4 h at 80oC) of GP mortar to enhance compressive strength of the mix containing different micro fibers (Bhutta et al., 2019). In general compressive strength of the mix contained PPF is higher than that of PET fiber subjected to heat curing. Also, there was no further first cracking strength enhancement with increasing PPF and PET fiber volume from 0.5% to 1%, and the post cracking residual stress was appreciably low especially for the mix contained PET fiber. Singh and Shah (2020) have tested FA and GGBS (50% each) based GPC contained PET fiber added to the mix by 0.25% and 0.5% (by weight). There was an enhancement of compressive strength by 9.03% and 12.7% and splitting tensile strength by 6.08% and 9.56% when using 0.25% for the mix tested at 7 and 28 days respectively. Shaikh (2020) investigated GPC containing PPF and PET fiber made of 20% slag and 80% FA subjected to ambient curing. The compressive strength of PET fiber reinforced GPC was found higher than its counterpart cement and cement-FA composites, while an increase in fiber volume from 1% to 1.5% showed a reduction in compressive strength. In contrast to other mixes, GPC reinforced by 1.5% PET fiber and PPF exhibited deflection hardening behavior in bending, but the flexural strength of PPF GP composite was lower than its PET fiber reinforced counterpart.

Slag, FA and a slag/FA combination for GPC mixes containing PPF were tested by Puertas et al. (2003). In the slag- based GPC, the addition of 0.5% and 1% PPF had no effect to change the compressive strength at the ages of 2 and 28 days, but in the FA based mix the 2-day compressive strength was found to increase with an increase of PPF content, in contrast to those specimens cured for 28 days. Further, GPC mixes prepared from a combination of FA and calcined kaolin with a ratio of 1:2 were tested by Zhang et al. (2009). Compressive strength was enhanced by 68% and 20% at the age of 1 and 3 days respectively was observed when using 0.5% PPF. The flexural strength was doubled with 0.75% PPF addition to the mix at both ages. In contrast to their observations, the flexural strength was not improved in the mixes tested by Puertas et al. (2003) when using PPF.

Baykara et al. (2020) tested natural zeolite GPC contained PPF. Nearly the optimum weight ratio of this fiber to enhance compressive strength is 0.5% and the strength enhancement was found to depend on the ratio of $Ca(OH_{2)}$ in the mix. Rajak and Rai (2019) tests showed a continuous compressive strength loss with PPF addition increase up to 0.3% reaching 15.41%, while modulus of elasticity's loss was 5.4% when using 0.5% fiber. A gradual increase in splitting tensile strength and flexural strength was observed with increasing PPF content reaching 29.56% and 21.53% respectively at 0.5% fiber compared with the control mix. Soeptivity was found to decrease from 77.81 m.s-0.5 to 57.96 m.s-0.5 with increasing fiber ratio up to 0.4%. After 56 days exposure to H_2SO_4 acid exposure, there was a relatively low weight loss of GPC mix with or without PPF (3.58% and 3.33%) compared with the OPC based concrete (14.47%). Compressive strength loss of 12.75% and 9.42% was observed for control mix and PPF contained mix respectively lower than the strength reduction of OPC concrete mix (28.96%) indicating a superiority of GPC with or without fiber for acid attack resistance. Tests by Behforouz et al. (2020) on metakaolin based GPC mixes with or without recycled aggregate indicate no serious change in compressive strength and water absorption when PPF is added to the mix by 0.3,0.5 and 1%, but a steady increase in flexural and splitting tensile strengths with increasing PPF up to 1% was observed. Wang et al. (2020) showed that for a FA based lightweight GPC, there is a strength enhancement when using 0.5% PPF by 47% as minimum, but there was a strength loss when using 19 mm fiber. Post peak compressive stress was well modified depending on the fiber length. Also, compressive strength of the mix reinforced with 0.5% fiber was larger than that of the mix reinforced with 1% and 1.5% for 3 mm and 12 mm fiber lengths. According to Al-mashhadani et al. (2018), 7 and 28 days compressive strength of the mix contained 0.4% PPF is slightly larger than that of control mix and the strength was found to decrease with increasing PPF up to 1.2%. They observed that compressive strength, modulus of rupture and flexural toughness of mortar with PPF are not enhanced well compared with those of the mix contained steel and PVA fibers. Other tests by Noushini et al. (2018) on GPC contained 0.5% PPF showed that the compressive strength, modulus of elasticity, modulus of rupture and post peak compressive strength response is not good, but some splitting tensile strength and flexural toughness enhancements was observed. Compressive strength by 16.6% on using 0.15% PPF addition to metakaolin based GPC mix was found by Moradikhou et al. (2020), and further increased when using 0.22% fiber but reduced when the fiber is increased to 0.25%. The performance of PPF was found good to enhance indirect tensile strength and modulus of rupture. Experimentally, Ganesh and Muthukannan (2019) observed a continuous compressive, splitting tensile and flexural strengths enhancement of the mix with increasing fiber up to 0.5% for GPC cured at ambient temperature. According to Arumugam et al. (2018), the best ratio of PPF

added is 2.5%, in which there is a compressive strength enhancement of 35.99% and 73.47% when compared to conventional concrete and GPC respectively at 28 days. These ratios were 23.74% and 13.40% for splitting tensile strength and were 52.47% and 44.24% for flexural tensile strength. Other tests by Mohammed et al. (2021) on metakaolin based GPC showed that there is a compressive strength, indirect tensile strength, and modulus of elasticity enhancements by 14.75%, 15.76% and 13.1% respectively when 1% of PPF is used, and the enhancement of the mentioned properties reduces with increasing PPF to 1.5%. Also, there was a an enhancement of modulus of rupture with increasing PPF ratio reaching 27.3% when using 1.5% fiber. Test data by Patil and Patil (2015) showed that the performance of 20 mm PPF to enhance different strengths is better than that of 12 mm fiber added to GPC by 1.5%. The maximum compressive strength, splitting tensile strength, flexural strength enhancement of 8.48%, 12.26%, and 19.25% respectively was observed. Experimental tests by Asrani et al. (2019) on GGBS based GPC reinforced with 0.3% PPF showed that there is compressive strength and modulus of rupture enhancements by 6.9% and 108.9% respectively. Using hybrid fiber to enhance strength and impact behaviors of GPC was found better than using single fiber. In a study, Bhutta et al. (2017) tested FA based GP mortar reinforced with 0.5% of 50 mm length PPF. Compressive and flexural tensile strengths were higher for specimens subjected to heat curing and the performance of PPF is not good as that of steel fiber especially for the post peak residual strength and toughness.
Ullah Khan and Ayub (2021) studied geopolymer composite without and with 2% PET fiber and the properties were compared with the composites contained polyvinyl alcohol (PVA) and polypropylene (PP) fibers. Bending, compression, and direct tension to observe the multiple cracking and pseudo-strain-hardening response were investigated. Mechanical properties of GP composite containing PET fiber was better among all combinations, and this composite was found competitive to PVA fiber–reinforced composite in terms of strength and multiple cracking pseudo-strain-hardening response. Chindaprasirt et al. (2021) studied high calcium fly ash geopolymer paste reinforced with PPF added by 0, 0.5, 1.0 and 1.5% (wt of fly ash). The 10 M NaOH, Na_2SiO_3/NaOH ratio of 2.0, and liquid/binder ratio of 0.60 were used. The use of PPF at 0.5% wt of fly ash resulted in the best improvement in compressive strength while for modulus of rupture 1.0% was the optimum addition. A compressive strength enhancements were 4.9%, 11.8% and 11.5% for specimens tested at 7, 28 days respectively. With regard the flexural strength, at the age of 7 days, the peak loads enhanced by 14.1, 84.8 and 33.7% because of using 0.5, 1 and 1.5% fiber respectively. The flexural strength enhancement were 28.3, 91.8 and 48.5% for specimens tested at 28 days and were 34.3, 124 and 67.3% at the age of 90 days for specimens contained 0.5, 1.0 and 1.5% fiber respectively.
Rani et al. (2022) concluded that under exposure, compressive strength loss decreases with increasing PP fiber addition up to a limit of 0.6%. Also, PP fiber improves the performance of geopolymer concrete by resisting the chloride penetration.

More recently, Waqas et al.(2024) investigated the individual and combined effect of bentonite (added by 10% replacement of fly ash) and PPF (added by 0.5, 0.75 and 1%) on the workability, mechanical properties, and durability of fly ash based GPC. Water absorption, acid attack, and abrasion resistance tests were used to evaluate durability. The results showed that bentonite and PPF significantly enhance mechanical properties, especially when combined with treated bentonite, with the highest improvement observed for mixtures with 1% PPF. The compressive strength was improved by an extent of 10% and 18% compared to the control mix without bentonite. The durability test results revealed that water absorption at the age of 90 days was decreased by 16% and 21%, while the mass loss of bentonite-GPC mixtures in sulphuric acid solution was 5% and 10% lower and also the abrasion resistance was 6% and 12% lower. They concluded that for durability performance, mixtures with 0.5% PPF perform the best action. In an experiment, Sangi et al. (2024) investigated indirect tensile strength and modulus of rupture of fly ash-GGBFS based GPC activated with Na_2SiO_3 contained dosages of PP fiber added by 0.2%, 0.4%, 0.6% and 0.8%.

There was a consistent augmentation in compressive strength with the incremental addition of fibers up to a threshold of 0.6%; but beyond this point, compressive strength deteriorated. According to their results, modulus of rupture and indirect tensile strength were enhanced from 25% to 45% with the addition of an optimum dosage of PP fiber.

The practical application of geopolymer concrete is limited due to its high shrinkage strain and high brittleness compared to OPC concrete (Waqas et al., 2024). Researchers have attempted to use PPF to improve the mechanical properties of geopolymer concrete via reducing drying shrinkage and enhancing ductility. Al-mashhadani et al. (2018) found experimentally that drying shrinkage is well reduced with the addition of 0.4% PPF but increases with increasing the fiber ratio up to 1.2%. In a study on geopolymer paste, Rani et al. (2022) concluded that drying shrinkage of geopolymer paste can be minimized by the addition of polypropylene fiber. Totally, there is a need for further experiments to learn more about shrinkage of GPC containing PET fiber or PPF or combination of both fibers.

Reviewing literature indicates that the experimental works on properties of GPC containing PA and PET fiber, in contrast to that containing PPF are limited, and there is a vital need to perform other experimental studies to highlight more the performance of modified concrete with these wastes addition. In this study, properties of compressive strength, flexural tensile strength, drying shrinkage and resistance to sulphate solution attack of FA based GPC containing PET waste aggregate and PET waste fiber were investigated experimentally. Also, the mentioned properties of GPC reinforced with PPF were investigated to compare the performance of concrete with that containing the two PET wastes.

2. Materials and methods

2.1 Materials

ASTM class F fly ash (FA) delivered by Eurobuild Company- UAE of specific gravity equal to 2.12 was used in this study. Fig. 1 shows fly ash powder used in this study. To activate the fly ash used in concrete, alkali activator solution (AAS) which was a mixture of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) was used. Sodium hydroxide used in this study was in a form of flakes prepared by Chemi company (see Fig. 2). NaOH was dissolved in water to obtain a 10 molar liquid of density equal to 1333 kg/m^3, while Na_2SiO_3 of density equal to 1581 kg/m^3 was used. Fine aggregate (FAg) of 1654 kg/m^3 compacted dry density, fineness modulus of 3.47 and specific gravity of 2.86 and coarse aggregate (CAg) of specific gravity equal to 2.61, compacted density of 1504 kg/m^3 and maximum size equal to 12.7 mm were used. Grading of the two aggregates are shown in Fig. 3, from which one can observe that both aggregates conform to the limits of ASTM C 33 specification (2016). Potable water was used to prepare the alkali activator solution. The plastic aggregate (PA) used in this study was polyethylene terephthalate (PET) waste aggregate of regular size particles prepared from post consumed liquid container bottles. This plastic aggregate was 5 mm square shape flakey particles of 0.4 mm thickness. The plastic flakes is shown in Fig. 4 and used in the mixture as fine aggregate replacement. The PET waste fiber (see Fig. 5) was also taken from plastic bottles. Average length of fiber was 20 mm, width was 1.5 mm and thickness was 0.4 mm. Specific gravity of the PET waste material was found to be 1.2. Further, monofilament type polypropylene fiber (PPF) shown in Fig. 6 used in this study was prepared by Belmix company and was of 0.9 specific gravity, 50 microns diameter and 12 mm length.

2.2 Test variables

Five different concrete mixes were designed to examine the fundamental properties of GPC containing PET waste aggregate, PET waste fiber and PPF. Based on the information available in the literature when using plastic waste aggregate and plastic waste fiber in concrete, a PET waste aggregate was fixed to be 5% as sand replacement. PET waste fiber and PPF ratio was kept to be 1% by volume, while a special concrete mix was prepared reinforced with hybrid fiber (50% PET fiber and 50% PPF). The aim of this arrangement is to produce a GPC of good properties suitable for structural and nonstructural applications, but there is a vital need for further studies on this topic. Laboratory tests were conducted on 100x200 mm cylinder specimens to measure dry density (γ_c) and compressive strength (f'_c), while flexural strength (f_r) and drying shrinkage (ε_{sh}) tests were carried out on 100x100x500 mm prisms. 100x100x100 mm cubes were used to study the sulphate resistance of GPC. All tests were done at the ages of 7 and 28 days following initial heat curing.

2.3 Mix design

In the current experiment, compressive strength of control mix (without fiber or plastic aggregate) was kept to be 30 MPa. Aggregate maximum size was 12.7 mm; Na_2SiO_3/NaOH was kept to 1.5, while fine aggregate ratio of 30% of total aggregate was used. Geopolymer concrete mix design for control mix were made following the procedure described by Phoo-ngernkham and Phiangphimai (2018), and the following results were obtained.

Water content = 215 kg/m^3.

% voids = 2.5%

Adjusted AAS based on voids in FAg. = 124.1 kg/m^3.

Total AAS = 215+124.1= 339.1 kg/m^3

For f'_c = 30 MPa, alkali activated solution/fly ash (AAS/FA) is kept to be 0.5.

Na_2SiO_3 = 203.46 kg/m^3

NaOH = 135.64 kg/m^3

FA = 339.1/0.5 = 678.2 kg/m^3

CAg= 776.48 kg/m^3

FAg = 364.65 kg/m^3

The values given above are for control mix without plastic aggregate, PET plastic and PPF. In one mix, fine aggregate is replaced with 5% PET waste aggregate by volume (Mix MPA). 1% PET fiber was added to concrete in mix MPETF, 1% PPF was added to concrete in mix MPPF), while in mix MPAPETFPPF, 5% PET aggregate, 0.5% PETF and 0.5% PPF were added. Table 1 shows the amount of material per cubic meter of concrete.

2.4 Mixing, casting and curing

Mixing process was performed following the procedure given below. Firstly, for the control mix dry materials (fly ash, coarse aggregate and fine aggregate) were fed into the electrical tilting drum of 0.16 m^3 capacity mixer and left to mix for two minutes. Later, alkali activator solution was added followed by 50 kg/m^3 additional water to enhance workability since no chemical admixture has been used and left to mix for another three minutes. For GPC mixes with fiber or PET waste aggregate, after mixing fresh concrete, the fiber or plastic aggregate was sprayed on the fresh concrete while mixing and left to mix for another two minutes.

With regard to molds, plastic cylinders and steel prisms were used, of inner surfaces thoroughly oiled to facilitate demolding. After 24 hrs from casting, specimens were taken from molds and the first measurement for axial strain of prism specimens was recorded. All specimens were put inside the oven and subjected to heat curing at 80^{o}C for 24 hrs. Later, the specimens were taken from the oven and left to cool down in the laboratory and another measurement of the axial strain was taken for drying shrinkage. All specimens then subjected to curing at the ambient temperature of about 25^{o}C for 7 and 28 days and then tested for shrinkage, density and mechanical properties.

2.5 Measurements and instrumentation

Dry density test was carried out on 100x200 mm cylinder specimens at the age of 28 days. Both compressive strength test and flexural strength test were done using the universal testing machine of CONTROLS-Italy model (Channel I for compression and Cannel II for flexure) shown in Fig. 7. Compressive strength test was performed on 100x200 mm cylinder specimens according to the recommendation of ASTM C39 specification (2012) under loading rate of 0.5 MPa/s. Few days before testing, top surface of all cylinders were capped using high strength gypsum to ensure smooth surface. Modulus of rupture tests were performed on 100x100x500 mm concrete prisms according to ASTM C78 specification (2010) recommendation. With regard the drying shrinkage test, a special fabricated steel holder shown in Fig. 8 was used. The prismatic specimen was located vertically and the strain was measured frequently at different times in the laboratory at about 25 ^{o}C degree, in which the end point of the dial gage (accuracy of one micron) is attached on the top surface (see Fig. 8). To measure shrinkage strain, the deformation is then divided by the specimen's length (L). In order to perform acid attack test, cube specimens subjected to 28 days curing and drying for 7 days were immersed in 5% sulfuric acid solution with the pH ranging from about 1.4 to 2.3 up to a period of 30 days of exposure. The specimens were removed from the acid solution container, wiped clean, left to dry for 7 days and then tested. The acid resistance of GPC was assessed through visual appearance, change in weight and compressive strength change after immersion for 7 and 28 days.

3. Test results and discussion

Results obtained from different tests conducted on GPC specimens are shown in Table 2. Below, test results and discussion, in some detail are presented.

3.1 Dry density

Fig. 9 shows variation of density for different concrete mixes. Density ratios for tested specimens MPA, MPEF, MPPF, and MPAPETFPPF are 0.966, 0.947, 0.930 and 0.931 compared with control specimen tested at 7 days respectively, while for those specimens tested at 28 days the ratios are 1.0, 0.996, 0.998 and 1.012. Dry density of GPC at the age of 7 days reduces with the inclusion of PET waste aggregate and PET waste fiber by 7% as maximum value, occurred because of plastic's low density. Also, there is a weight loss as a result of adding PPF to GPC mix. This weight loss may be due to using a relatively large volume of PPF (i.e. 1%) that may cause some internal cavities inside the concrete mass due to balling effect of the fiber during mixing, in addition to low specific gravity of PPF. Results also show that there is a small action of using PET waste aggregate and fiber and also PPF on the 28 days dry density. The obtained results support those observed by Akcaozog˘lu and Ulu (2014) that used shredded flakey PET waste aggregate and by Wongkvanklom et al. (2019) that used recycled plastic beads.

3.2 Compressive strength

Fig. 10 shows variation of compressive strength for different concrete mixes. Compressive strength ratios for tested specimens MPA, MPEF, MPPF, and MPAPETFPPF are 0.909, 1.050, 1.160 and 1.098 compared with control specimen tested at 7 days respectively, while for those specimens tested at 28 days the ratios are 0.983, 1.164, 1.160 and 1.098. From the results of Fig. 10, as compared with that of virgin mix, there is a compressive strength loss of GPC when fine aggregate is replaced with PET waste aggregate by 9.1% and 1.7% at the ages of 7 and 28 days respectively. One can find a recovery of compressive strength loss with time. This phenomenon could be attributed to the slow reaction of fly ash with time able to fill small flaws and cavities, especially between hardened paste and PET aggregate surface produced at the early stages of hydration. On this base one can conclude that using 5% PET waste aggregate has small effect on the compressive strength and could be added to the GPC mix to produce a plastic waste aggregate recycled geopolymer concrete. In general, the strength loss is lower than that observed by Akcaozog˘lu and

Ulu (2014) in which they worked on the slag/metakaolin based GPC, and observed by Manjunatha et al. (2018) that used GGBS as a source binder, indicating that the source pozzolanic material has an effect on the residual strength of GPC containing PA. The difference could be attributed to the fact that lower ratio of PA was used in the current study. The obtained results are compatible to those obtained by Lenin Sundar and Raj (2017) that found a strength enhancement.
Results showed a compressive strength enhancement when PET fiber is added to GPC by 16.4% as maximum value when using 1% PET fiber in GPC tested at the age of 28 days. This strength enhancement is close to that of GPC containing PPF indicating the suitability of PET waste fiber obtained from simple recycling. Results show that increasing curing time more than 7 days has no effect to enhance strength of GPC reinforced with PPF. It will be also noted that hybridization of the two fibers (PPF and PET fiber) is not useful to enhance compressive strength more, and it is better to be used separately. According to Fig. 11, for control concrete and concrete mix containing PET waste aggregate, there is a relatively large amount of cracks and disruption of concrete near failure, while for those specimens containing PET fiber and/or PPF the situation is different. Existence of these plastic fibers is able to bridge narrow cracks and prevent extension and separation pieces of concrete under compression. This behavior is identical to that of normal concrete reinforced with PET waste fiber (Mohammed and Mohammed, 2021).
The results of compressive strength enhancement because of PET fiber addition is compatible to those obtained by Singh and Shah (2020), but these researchers have used smaller volume of recycled PET fiber of geometry close to that of PPF.
According to the data obtained, there is an enhancement of 28 days compressive strength by 16.4% on PPF addition by 1%. Compressive strength enhancement because of PPF was observed by the majority of investigators worked on GPC discussed in the literature review, but Puertas et al. (2003), Noushini et al. (2018) and Behforouz et al. (2020) found no serious action of PPF. The strength enhancement observed in the current study agreed well with the test data obtained by Baykara et al. (2020), Arumugam et al. (2018), Asrani et al. (2019), Mohammed et al. (2021), Chindaprasirt et al. (2021), Waqas et al. (2024) and Patil and Patil (2015). Further, reviewing past studied indicates that the PPF ratio close to 0.5% is a critical ratio.

3.3 Modulus of rupture

Fig. 12 shows variation of modulus of rupture for different concrete mixes. Modulus of rupture ratios for tested specimens MPA, MPEF, MPPF, and MPAPETFPPF are 0.921, 0.956, 1.144 and 0.974 compared with control specimen tested at 7 days respectively, while for those specimens tested at 28 days the ratios are 0.900, 0.956, 1.144 and 0.965. From the results of Fig. 12, one observes a reduction in modulus of rupture by 8% and 10% at 7 and 28 days respectively when PET waste aggregate is added by 5% as sand replacement. The flexural tensile strength loss was also observed by Akcaozogˇlu and Ulu (2014), Wongkvanklom et al. (2019) and Lazorenko et al. (2022). Lower modulus of rupture loss by 4.4% is observed on using PET waste fiber. Unfortunately, there is no chance to compare the data obtained with those of Bhutta et al. (2019) and Shaikh (2020) because of the absence of control mix to measure the change. However, these researchers found no further strength enhancement as the PET fiber increased from 0.5% to 1%.
In contrast to the action of PET waste aggregate and fiber, there is a modulus of rupture enhancement by 14.4% because of 1% PPF addition to GPC, while hybridization of PET fiber and PPF is not a useful process to enhance modulus of rupture mainly because of the existence of PET aggregate. Komonen and Penttala (2003) and also Urbanova et al. (2007) reported that during tension PPF stretches themselves to accommodate the crack face separation thus providing an extra energy absorbing mechanism which may have an action to enhance flexural strength of GPC. In general, there is a flexural strength enhancement of GPC due to PPF addition (Zhang et al., 2009, Rajak and Rai, 2019, Behforouz et al., 2020, Al-mashhadani et al., 2018, Arumugam et al., 2018, Patil and Patil, 2015, Moraddikhou et al., 2020, Ganesh and Muthukannan, 2019, Mohammed et al., 2021, Asrani et al., 2019, Chindaprasirt et al., 2021, Sangi et al., 2024), however there are some

records (Puertas et al., 2003, Noushini et al., 2018) indicate no an appreciable effect of PPF to enhance flexural strength.

Fig. 13 shows modulus of rupture- deflection relationship, from which one can find a different response for both ascending and descending branches. The slope of the ascending portion is increased with the modification made on control GPC, and the highest slope is for the specimen reinforced with hybrid PPF-PET fiber. However, this increase in flexural stiffness is not accompanied with the flexural strength enhancement. One can observe that deflection corresponding to maximum flexural strength is reduced well as a result of adding PET fiber or PPF to concrete. Also, there is a modification of the post-peak branch of the relationship due to the fiber existence, and there is a residual stress for those mixes containing PPF, not been existed for mixes with PET aggregate or PET fiber. As observed from Fig. 14, failure of prisms for MC and MPA mixes was sudden and the specimen was separated to two pieces, not been observed for the other three mixes. After formation of a single crack at the central zone, there was a bridging of the two parts of the specimen, left and right of the central crack PET fiber and PPF existence. The performance of PPF on this mode of failure was found better, mainly because of smaller dimension and well dispersion of the fiber inside the mix.

3.4 Drying shrinkage

Table 3 shows results of drying shrinkage strain of specimens for different ages up to 30 days and the results are also illustrated in Fig. 15. There is a relatively high shrinkage strain because of initial heat curing in furnace and cooling down of specimens (instantaneous drying shrinkage). One can find a relatively high instantaneous drying shrinkage of GPC mix containing PET waste aggregate and further increase of shrinkage strain with time. This behavior should be addressed well and the authors think that there is a need for further studies on this topic. Also, with the elapsed time there is a small change in the drying shrinkage up to 30 days except for MPA mix, in which there is a continuous shrinkage strain increase. Perera et al. (2007) reported that GPC shrinks excessively during heat curing, and this excessive shrinkage may lead to the formation of micro cracks. PPF in the GPC matrix has a beneficial effect since it reduces the probability of formation of micro-cracks because of plastic shrinkage given more flexural strength to the composite. From the results of Fig. 15, one can find that performance of PET fiber is better than that of PPF and the addition of PA to the combination of both fibers will lead to further shrinkage strain reduction. Totally, there is a need for further research to be carried out on the action of the three materials added to GPC attempted in this study.

3.5 Sulaphate attack resistance

No significant change in appearance was found after immersion GPC samples in the sulphate solution and drying. However, non uniformly distributed whitish deposit smears was observed on the surface of majority of specimens and the color was changed from the characteristic gray to light gray one. Results of weight loss and compressive strength change of different concretes after 28 days immersion in H_2SO_4 acid solution are presented in Table 4. Fig. 16 illustrates variation of weight loss for different specimens while Fig. 17 shows variation of the residual compressive strength after 7 and 28 days exposure. One can find 3.01% weight loss of control concrete due to the acid exposure, but this weight loss reduces when the two PET wastes and PPF are added to the mix. According to the results presented in Fig. 17, there is 6.1% compressive strength reduction for control mix, and the strength loss will be 0.93% and 1.86% for the GPC mix containing PET waste aggregate and fiber respectively indicating a useful action of the shredded PET waste to resist sulphate attack. For the mix with PPF and hybrid PPF-PET fiber the strength losses of 5% and 5.52% are observed, and accordingly the performance of PET waste aggregate and fiber is close to that of PPF.

Bhutta et al. (2014) investigated durability of GPC exposed to a 5% sodium sulphate solution for more than one year. Weight loss and compressive strength enhancement was observed.

Compressive strength was found superior to that of OPC concrete and they concluded that GPC could be used for making sulphate-resistant concretes. Sulphate resistance was attributed to a more stable cross-linked aluminosilicate polymer structure formed in the concrete. Thokchom et al. (2010) found that after 24 weeks exposure to magnesium sulphate solution GP mortar samples suffered from weight change ranged between 0.42% and 1.98% and loss of compressive strength ranged from 10.3% to 56%. Further, Bakharev (2005) tested geopolymer paste exposed to 5% solutions of acetic and sulfuric acids. After two months exposure, there was 3.83% weight gain in the acetic acid solution and 2.56% weight loss in the sulfuric acid solution. Although, compressive strength loss reached 38.3% after 6 months immersion in acetic acid, the performance of geopolymer materials was superior to ordinary Portland cement (OPC) paste. A significant degradation of strength was observed in some mixes which was attributed to depolymerisation of the aluminosilicate polymers in acidic media and formation of zeolites. Totally, the performance of GPC with or without PET wastes and PPF subjected to sulphate solution up to 30 days seems to be good, but there is a need for further studies on this important topic of GPC and, when testing, the chemical solution exposure for longer periods should be maintained.

4. Conclusion

The issue of this experiment is interested since it deals with the properties of an important kind of sustainable environmental- friendly concrete, which is GPC contained plastic aggregate or fiber. From the results of this work, the following conclusions are drawn:

1- Dry density is reduced due to different PET wastes and PPF addition to GPC and reduction was found higher on using PET waste aggregate. There is a 7 days compressive strength loss of GPC by 9.13% when PET waste aggregate is added, but there is no serious strength loss at the age of 28 days. Compressive strength enhancement by 16.4% and 16% was observed when using 1% PETF and PPF respectively, and accordingly the performance of manually prepared PET fiber is close to that of the synthetic fiber.

2- There is a modulus of rupture loss by 10% and 4.38% on using PET waste aggregate and fiber in GPC respectively, while there is an enhancement by 14.4% on using PPF. Hybridization of PPF-PET waste fiber has no effect to enhance compressive strength or modulus of rupture. Flexural strength- deflection response ascending portion’s slope tends to increase with PET waste aggregate, PET waste fiber and PPF addition to concrete, while the descending portion was modified on using PPF or hybrid PPF-PET fiber. Accordingly, hybridization with PPF will improve the post-peak response of GPC contained PET waste fiber. Addition of PET fiber or PPF to GPC has the ability to control flexural cracking extension and change sudden collapse to a gradual failure.

3- In general, the instantaneous drying shrinkage of GPC reduces because of PET fiber and hybrid PPF-PET fiber addition to GPC and not changed well with the elapsed time up to 30 days. The shrinkage strain of concrete containing PET waste aggregate was found to be higher than that of control concrete and tends to increase more with time.

4- When GPC is subjected to sulphate solution, there is a weight loss by 3.01% but the weight loss is reduced when different PET wastes and PPF are added to GPC. No serious compressive strength loss was observed (only 6.1% as maximum) due to sulphate solution exposure up to 30 days. Addition of PPF and different PET wastes has some effect to reduce the strength loss, in which GPC containing PET waste fiber subjected to sulphate had the same strength of concrete before exposure.

5- The plastic materials added to GPC attempted in this study is limited to 5% for the PET aggregate and 1% for both PETF and PPF. These ratios were selected based on the literature review and one observes that the PA addition is accompanied with lower strength loss as compared with that observed by the past researchers. Majority of the properties of GPC were improved on using 1% PETF and PPF and accordingly there is a good chance to be used for GPC production.

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Table 1 Concrete mix constituents (kg/m^3)

Mix	FA	FAg	CAg	NaOH	Na_2SiO_3	PA	PETF	PPF
MC	678.2	364.65	776.48	135.64	203.46	-	-	-
MPA	=	346.42	=	=	=	13.23	-	-
MPETF	=	364.65	=	=	=	-	12	-
MPPF	=	364.65	=	=	=	-	-	9
MPAPETFPPF	=	346.42	=	=	=	13.23	6	4.5

MC= Control mix, MPA= Mix with plastic aggregate, MPETF= Mix with PET fiber, MPPF= Mix with polypropylene fiber, MPAPETFPPF= Mix with plastic aggregate, PET fiber and polypropylene fiber, FA= fly ash, FAg= fine aggregate, CAg= Coarse aggregate

Table 2 Results of testing different concrete mixes

Code	Density (kg/m^3)		Compressive strength (MPa)		Modulus of rupture (MPa)	
	7 days	28 days	7 days	28 days	7 days	28 days
MC	2147	2033	26.39	28.07	4.57	4.79
MPA	2074	2032	23.98	27.58	4.21	4.31
MPETF	2034	2025	27.71	32.68	4.37	4.58
MPPF	1997	2029	30.60	32.56	5.23	5.48
MPAPETFPPF	1998	2058	28.98	30.83	4.45	4.62

Table 3 Results of drying shrinkage strain

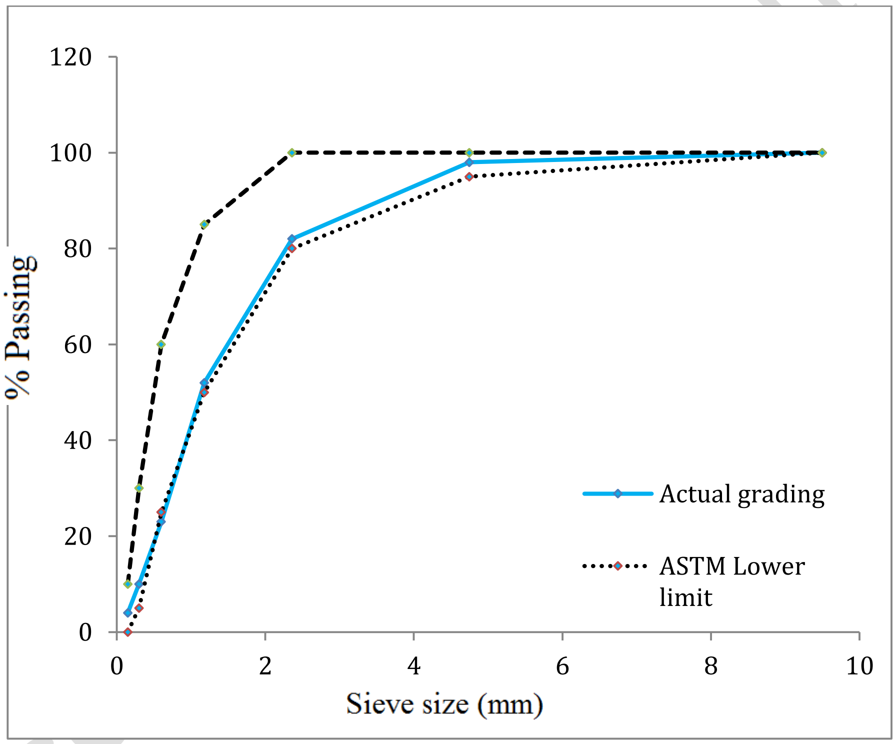
Specimen code	Drying shrinkage strain with age			
	1 day (after heating and cooling)	10 days	20 days	30 days
MC	-0.002145	-0.00252	-0.00155	-0.00115
MPA	-0.008575	-0.0102	-0.0109	-0.01204
MPETF	-0.00118	-0.00105	-0.00118	-0.00148
MPPF	-0.00193	-0.00241	-0.00247	-0.00248
MPAPETFPPF	-0.00093	-0.00072	-0.00081	-0.00102

Table 4 Weight loss and compressive strength of GPC mixes subjected to sulphate solution

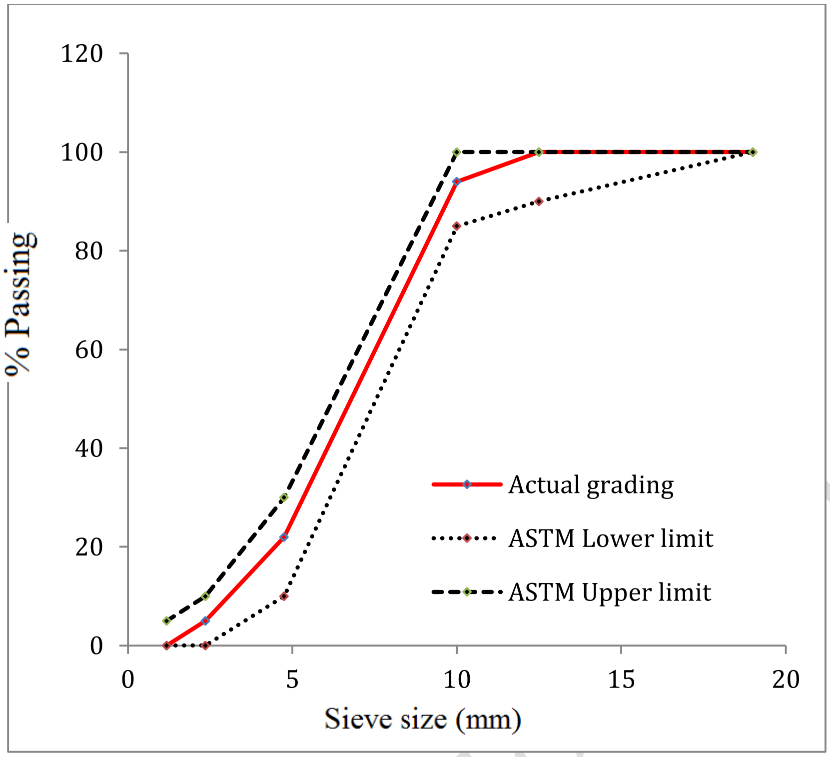
Specimen code	Weight loss (%)	Compressive strength (MPa)	
		Before exposure	After exposure
MC	3.01	33.60	31.55
MPA	1.04	33.19	32.88
MPETF	2.36	34.33	33.69
MPPF	1.22	34.17	32.46
MPAPETFPPF	1.43	31.52	29.78

Fig. 1 Fly ash

Fig. 2 Calcium hydroxide flakes



(a)



(b)

Fig. 3 Percentage passing curves (a) Fine aggregate (b) Coarse aggregate

Fig. 4 PET waste aggregate

Fig. 5 PET waste fiber

Fig. 6 Polypropylene fiber

Fig. 7 Universal testing machine for compression and flexure

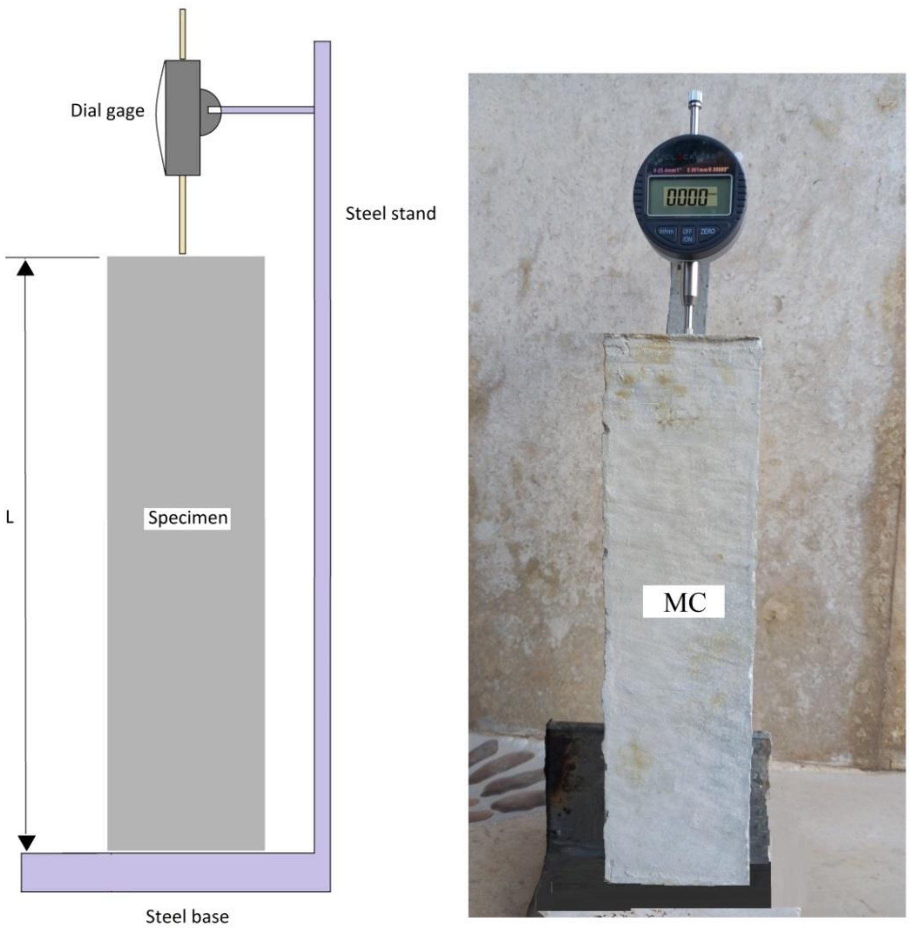


Fig. 8 Test device used for shrinkage measurement (a) Schematic side view (b) Actual front view

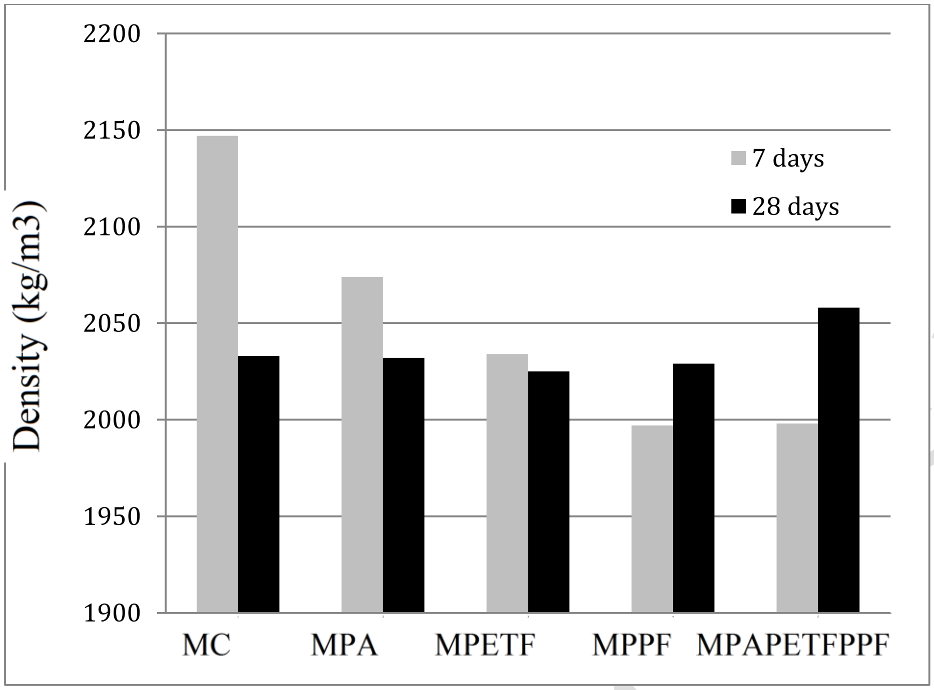


Fig. 9 Dry density for different concrete mixes

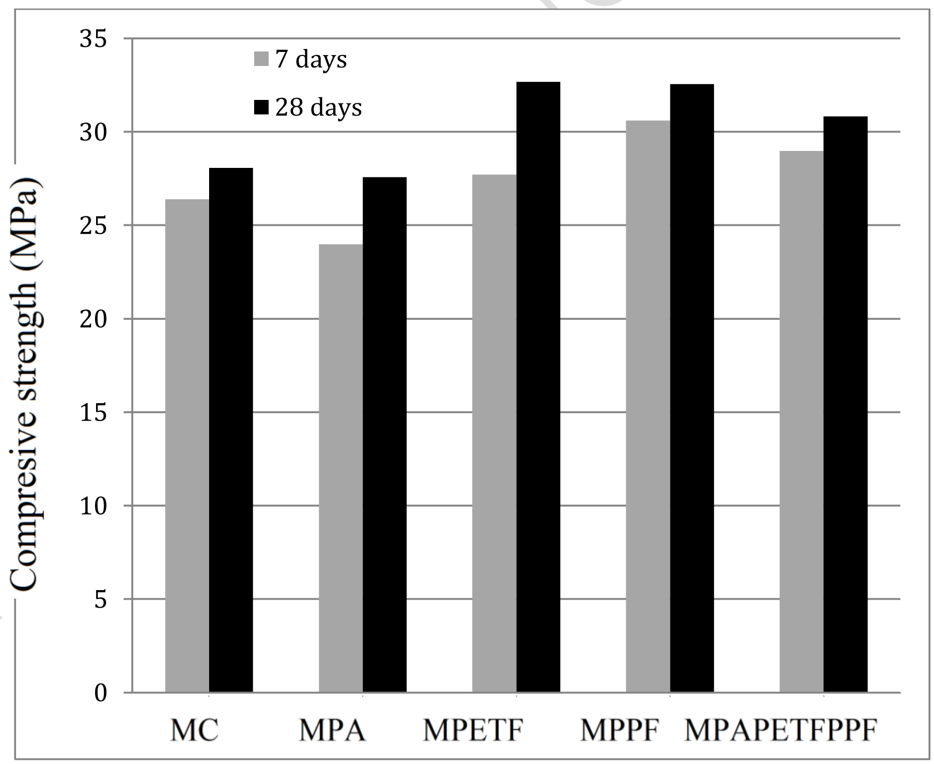


Fig. 10 Compressive strength for different concrete mixes

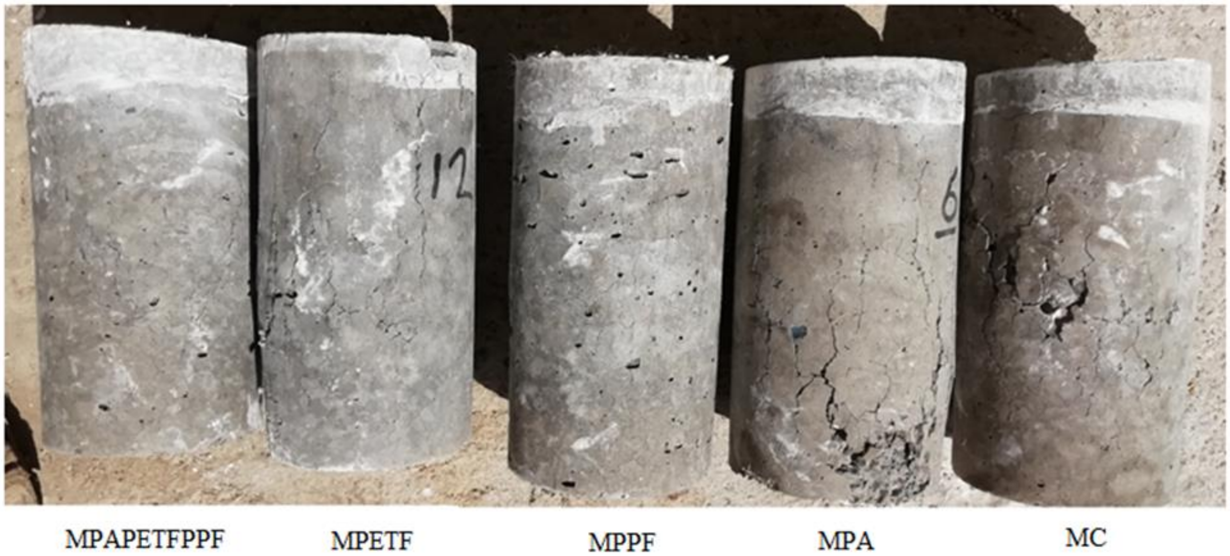


Fig. 11 Cylinder specimens after testing (7 days)

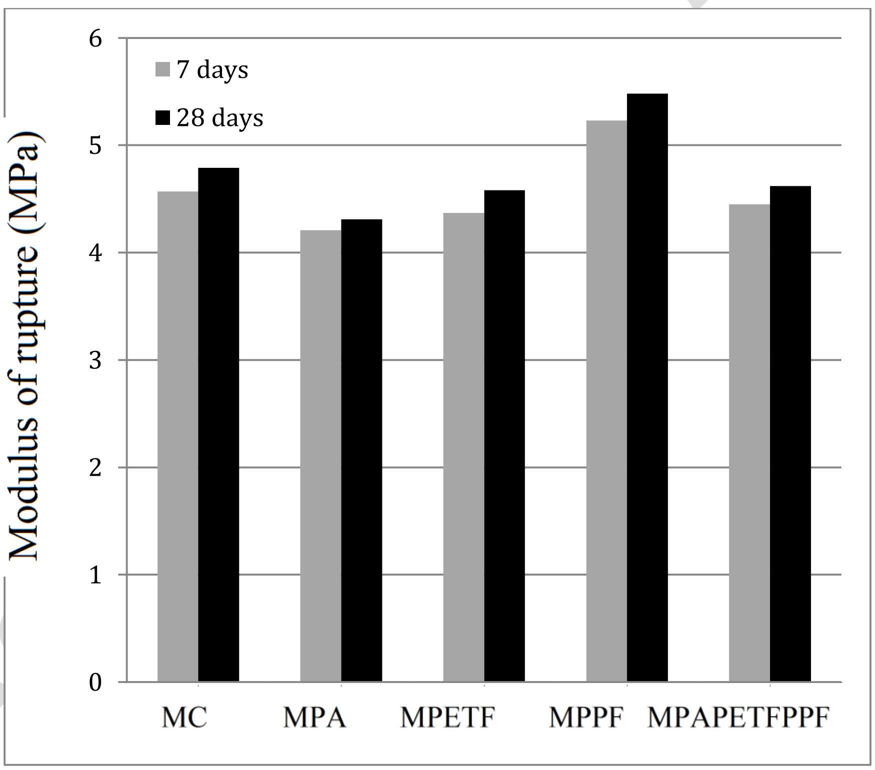


Fig. 12 Modulus of rupture for different concrete mixes

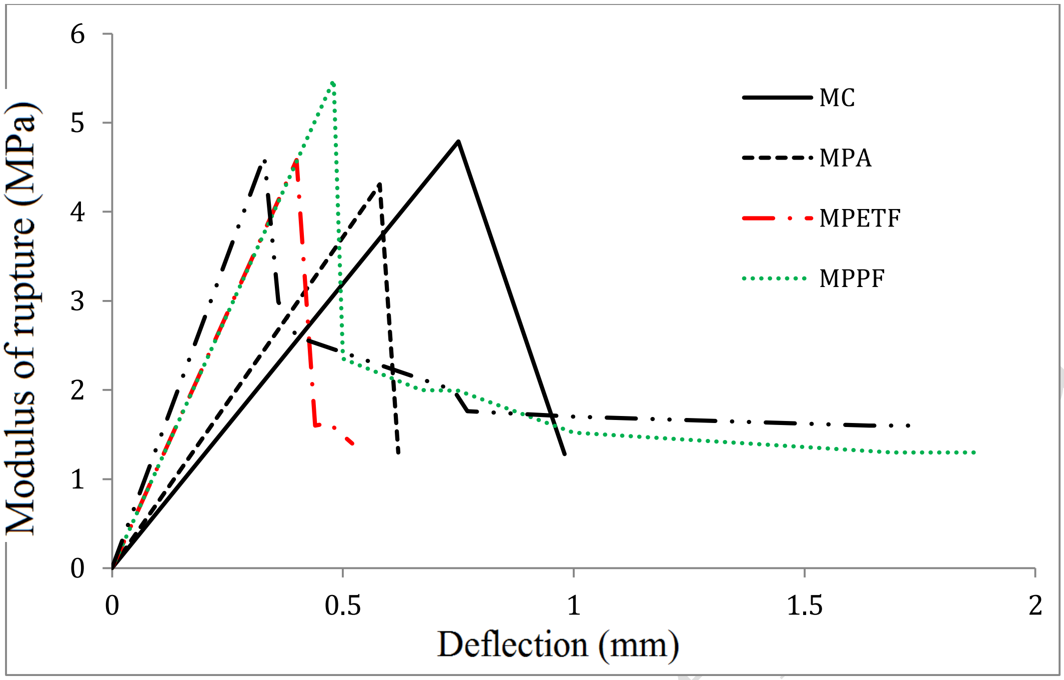
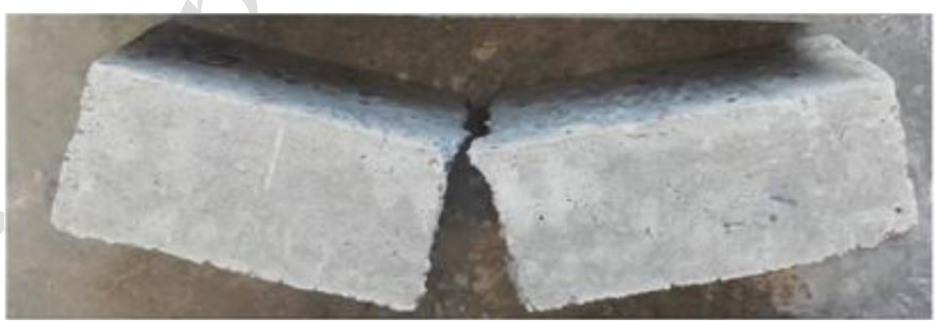
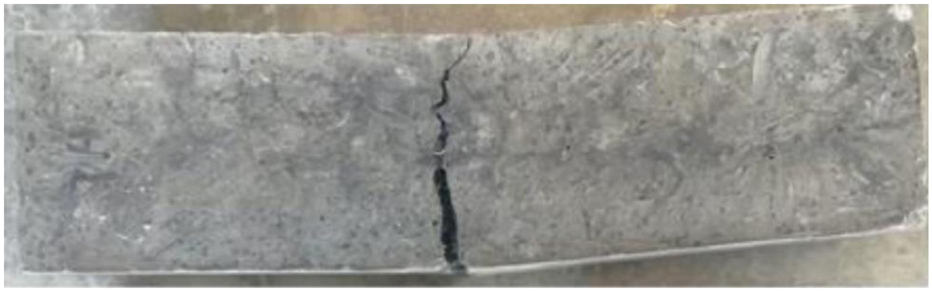


Fig. 13 Modulus of rupture- deflection relationship of tested prisms

MC



MPA



MPETF

MPPF

MPAPETFPPF

Fig. 14 View of prism specimens after testing

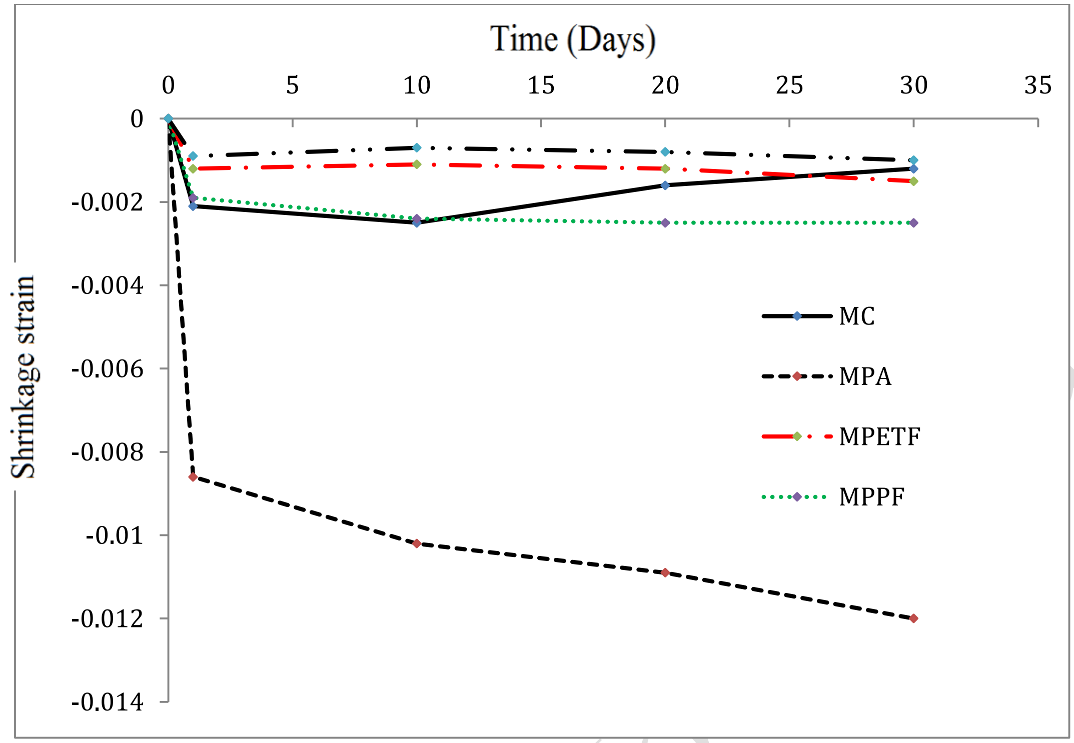


Fig. 15 Variation of drying shrinkage strain with time

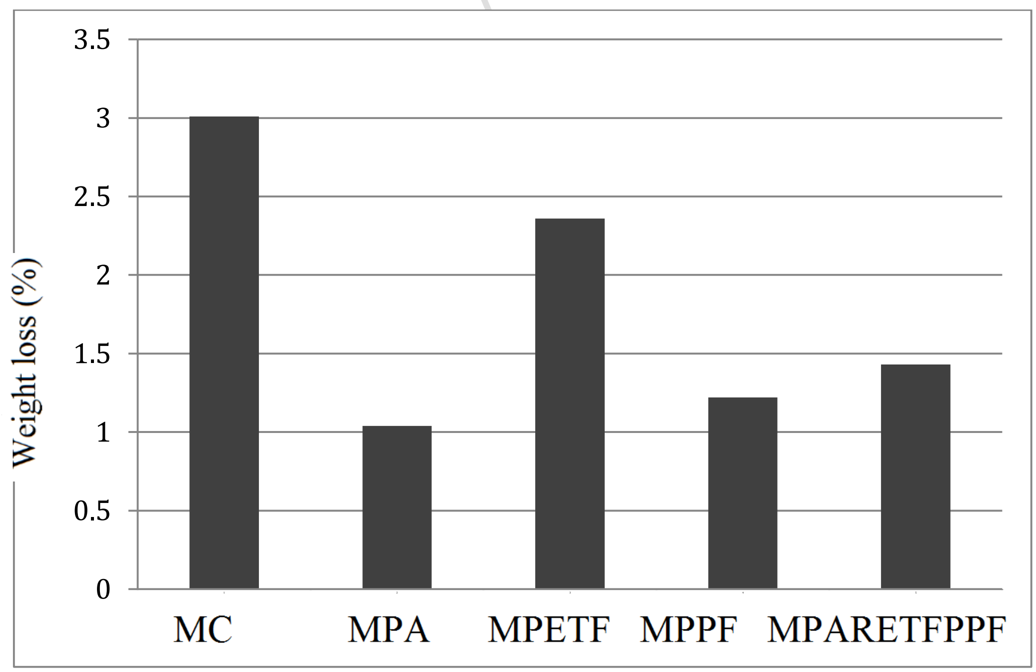


Fig. 16 Weight loss of GPC subjected to sulphate solution

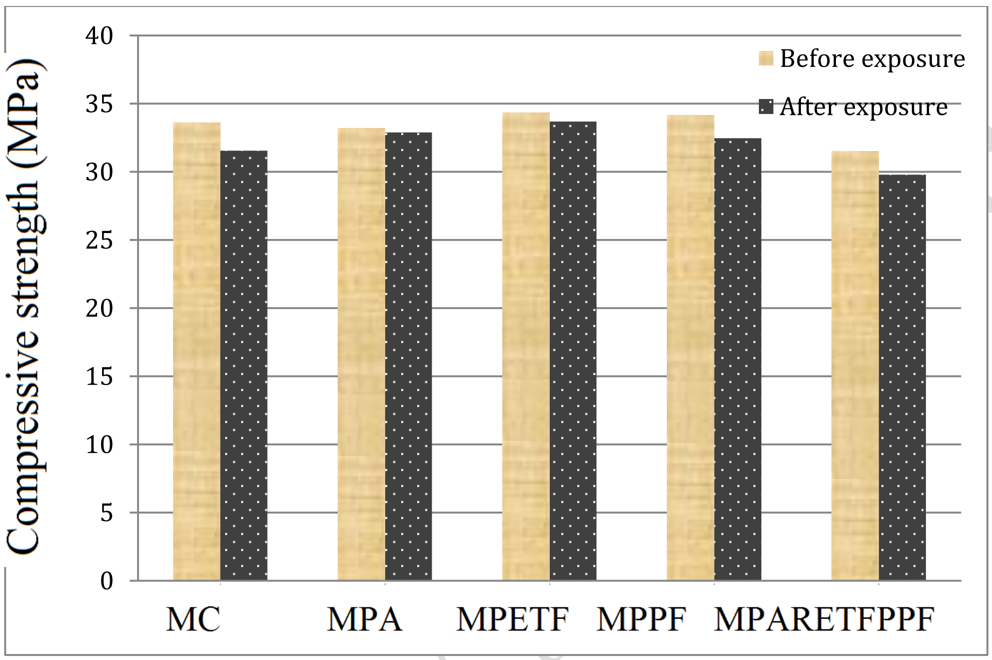


Fig. 17 Compressive strength of GPC subjected to sulphate solution