Journal of Material Cycles and Waste Management (2019) 21:1014–1026
https://doi.org/10.1007/s10163-019-00859-9

ORIGINAL ARTICLE

Utilization of metalized plastic waste of food packaging articles in geopolymer concrete

Ankur C. Bhogayata[1] · Narendra K. Arora[2]

Received: 30 August 2018 / Accepted: 28 March 2019 / Published online: 5 April 2019

Abstract
The metalized plastics are extensively used by the food packaging industry. The metalized plastic wastes (MPW) are largely unfit for reuse and recycle process and impose harmful impacts to the environment. The MPW may be sustainably utilized in construction materials. The fly ash-based geopolymer concrete (GPC) has emerged as a sustainable construction material in the past few decades. Therefore, a novel combination of MPW and GPC may hold the potential of preparing a greener and sustainable construction material. The objectives were to obtain the optimum dosage of MPW fibers and to evaluate the corresponding response of the fresh and strength properties of the modified GPC. To explore the effectiveness of the addition of MPW into GPC, the life cycle assessment was studied for MPW and the novel composite prepared by combining GPC and MPW. The results exhibited improvement of strength properties of modified GPC specimens due to MPW fibers with a reduced trend of improvement of workability. It was observed that an addition of 1% MPW fibers by volume of the mix showed good performance of the composite for all test conditions. The sustainability assessment of the novel composite demonstrated promising outcomes ensuring the feasibility of usage of MPW into the GPC.

Keywords Metalized plastic waste · Geopolymer concrete · Life cycle analysis · Sustainability

Introduction

A safe disposal and management of plastic waste by post-consumer activities have been a global challenge for environmental safety. With the constantly changing lifestyles and food habits of people, the usage of packaged food has shown outstanding growth in plastic usage. Out of total plastic production, about 39.9% of plastics are used by the packaging industry [1] and its growth rate is becoming higher with the time. On the other hand, according to a report, a safe disposal and management of plastic waste have remained a challenge for many countries till the date [2]. Moreover, not all the plastic wastes are fit for recycling or reuse namely the metalized plastic waste (MPW) generated from the refused food packaging articles and waste from packaging industries [3, 4]. They contribute to the continuous pollution being a part of the landfill and largely litter into the natural streams [5]. The metalized plastic consists of good durability and resistance to the chemical effects and may be utilized in the construction activities as one of the constituents. Efforts have been made to utilize MPW into the cement concretes [6–8]. The present study is an effort to extend the advantages of MPW utilization in one of the modern sustainable construction materials called geopolymer concrete.

Geopolymer concrete has emerged as the sustainable construction material as the preparation utilizes industrial wastes namely fly ash instead of conventional cement [9, 10]. To an extent, the fly ash-based geopolymer concrete is becoming an alternative to cement concrete [11, 12]. It may be worth exploring that the combination of MPW and GPC can be an innovative extension of making a sustainable construction material.

Literature shows that recycled plastic waste fibers have been successfully utilized as one of the constituents of the cement concrete. Extensive reviews are carried out by many researchers on the usage of recycled plastic fibers in cement concrete. It has been observed that the addition of plastic

✉ Ankur C. Bhogayata
ankur.bhogayata@gmail.com

Narendra K. Arora
narendrakarora@gmail.com

[1] Department of Civil engineering, Faculty of Engineering, Marwadi Education Foundation's Group of Institutions, Rajkot, Gujarat 360005, India

[2] L. E. College of Engineering, Morbi, Gujarat, India

fibers has improved the primary strength and durability properties of concrete. Specifically, the cracking resistance of concrete is improved due to the plastic fibers [13, 14]. In another literature [15], the researchers extensively reviewed the contribution of recycled plastic fibers on various concrete properties for strength, durability and fire resistance. The researchers presented a review [16] on use of recycled plastic in concrete. The review showed the potential for preparing precast concrete elements with recycled plastic aggregates. Moreover, the recycled plastic fibers may be mixed into the concrete for marine construction, pavement surfaces and damage repair works also.

A review article [17] discussed the addition of recycled organic components into the cement concrete. The review concluded that the fresh properties of concrete reduced with the addition of recycled plastic components but the durability, freeze–thaw resistance, impact resistance, and alkali–silica reaction were improved.

On the other hand, the geopolymer-based concrete is seldom explored for recycled plastic fibers. However, efforts are made to incorporate recycled aggregates in GPC and improvement of compressive strength is noticed [18]. Moreover, the GPC is prepared by utilizing the local pozzolanic materials for making it more sustainable [19]. Efforts are made to produce geopolymer by utilizing the Sago pith waste ash to improve the compressive strength of the matrix [20]. Effects of rock wool waste have also been explored by the researchers to make the GPC effectively sustainable [21].

Innovative use of recycled polyvinyl alcohol fibers (PVA) is utilized to improve the corrosion resistance of GPC containing steel reinforcing bars [22]. The short PVA fibers with varying sizes were added into GPC and the mixes were evaluated for flexure, fracture toughness, compressive strength, tensile strength and impact resistance [23]. Excellent improvement of GPC response to the flexure and fracture toughness was reported. Moreover, the researcher noticed the improvement of impact resistance and cracking resistance of the hardened GPC due to the addition of PVA.

Explorations discussed on the influence of PVA on bond strength of geopolymer-based repair mortar and concluded that the cohesion of the mortar increases up to 65% due to the presence of PVA in geopolymer-based mortars compared to the cement-based mortar [24].

A study was conducted on hybrid reinforcing fibers with steel and polypropylene (PP) fibers into geopolymer matrix [25]. Improvement of flexure behavior and load–deflection relationship was noticed due to the presence of the hybrid fiber reinforcement. In another work, the researchers extensively studied the effect of a geometrical attribute of the PP macro-fibers on splitting tensile strength, flexure strength, compressive strength and flexure toughness including the microstructural investigations. They noticed improvement of the properties up to 35% at the lower dosage of 0.5% of the fibers. However one of the major concerns of the fibers was the surface smoothness of the PP fibers as observed from the study [26].

The effect of PP fibers on the strain hardening and deflection characteristics of GPC cured at ambient temperature was investigated [27]. The work explored the surface adherence of the PP fibers with the hardened mass of GPC and showed excellent improvement of the load carrying capacity at the dosage range of 0.75–1% by the volume fraction of the mix. The synthetic fibers made from the high strength polyethylene (HSPE) were added into the geopolymer composite. The extensive study of the composite containing HSPE showed that the workability reduces, but the load carrying capacity of the composite increases due to the fibers.

The plastic wastes collected with PET, PP, PE bases are recyclable and can be reused, however, the MPW are unfit for effective recycling and reuse [28]. Moreover, the pollution due to MPW has remained a challenge even after a sensible increase in environmental awareness and consumer's initiatives [29]. The MPW have not been utilized in GPC to a sufficient extent and require attention by the researchers for the exploration.

The present study focuses on the feasibility of the utilization of MPW into GPC mixes. The study may exhibit double advantages of improvement of the material properties of GPC and as an alternate way of the disposal of the hazardous MPW responsible for everlasting pollution to the surrounding environments. In the present study, the MPW was rendered into the fibers and mixed into the GPC with varying volume fractions. The specimens were tested for workability and strength properties as a preliminary investigation program. The response by the modified GPC was studied for evaluating the feasibility of usage of MPW in the production of GPC. The results showed excellent improvement in the strength and acceptable changes of the workability response with 1% of MPW fibers in GPC.

Research significance

The present preliminary investigations on workability and strength properties of modified GPC were carried out to answer the following queries;

- What should be the optimum dosage of MPW in GPC mixes?
- What are the impacts of the addition of MPW on the fresh and strength properties of GPC?
- Is the addition of MPW in GPC beneficial for extending the sustainability of the conventional GPC?
- What are the environmental concerns of the addition of MPW in GPC?

The efforts have been made to answer the above queries by conducting the experimental investigations on specimens prepared with varying fractions of MPW fibers in GPC and evaluating the modified GPC based on LCA and sustainability analysis.

Experimental program and tests

Materials and specimens

Materials for GPC mix

The conventional GPC mixes were prepared using class F fly ash as a full replacement of cement. The chemical constituent details of class F fly ash are shown in Table 1. The alkaline activators were produced by mixing sodium hydroxide (NH) and sodium silicate (NS). The ratio of NH to NS was maintained at 2.25 according to the reference literature [30, 31]. The solution of NH was prepared by diluting the NH pellets into the distilled water with the concentration of 16 M. The solution of NS contained chemical composition as sodium oxide (Na_2O) and silicate oxide (SiO_2) as 14.46 and 32.53% of the solution with 53% water. To avoid the flash setting in the alkaline solution and to improve the workability of the mix, the superplasticizer from the FOSROC make ConPlast SP 430 AL was used. The heat curing temperature was maintained at 100 °C for 24 h for all the test specimens. All heat-cured specimens were allowed to ambient curing temperature (room temperature about 35 °C) for 28 days before testing.

The GPC was prepared with aggregates of two sizes namely 10 mm and 20 mm from the local sources in the surface dry condition. The 20 mm size aggregates having fineness modulus of 7.59 and water absorption 0.6% was taken 24%, 10 mm size coarse aggregate having fineness modulus of 5.75 and water absorption 0.8% was taken 46% and fine aggregate having fineness modulus of 2.28 and water absorption 1.4% was taken 30% for concrete mix for all batches.

Metalized plastic waste (MPW) fibers

The raw material for obtaining fibers from the metalized plastic films used by food packaging industry was obtained from a plastic packaging industrial unit located at Rajkot city of Gujarat. The film was of the polypropylene-based metalized thin film with a layer of aluminum on a one side surface. The general properties of MPW are listed in Table 2. The process of obtaining fibers form the sheet is illustrated in Fig. 1. The fibers were shredded in a shredder machine capable of producing the fibers of the average size of 1 mm width and 20 mm length. The dimensions of the fibers were decided from the research outcomes of the work carried out by the authors for the cementitious concrete [6, 7]. The MPW fibers were mixed in varying proportions of 0%, 0.5%, 1%, 1.5% and 2% by volume of the GPC.

Mixes and test specimens

Total five batches of GPC mixes were prepared. Each batch of GPC was prepared by varying the fraction of MPW fibers namely 0–2% at a 0.5% increment infraction. The mixes were designated according to the MPW fiber contents namely GPC0–GPC2. The results obtained from the specimens prepared with GPC0 were utilized for comparative study and considered as the reference mix. Details of the mixes are shown in Table 3.

To obtain the strength properties of hardened GPC, four types of specimens namely cube of 150 mm × 150 mm × 150 mm, a cylinder of 150 mm diameter and 300 mm height, beams of 150 mm × 150 mm × 700 mm and disk of 150 mm diameter and 65 mm thickness were prepared with a varying fraction of MPW fibers. Total 60 specimens were prepared and tested. The final test result was taken as an average value of test results of three specimens

Table 1 Chemical constituents of class F fly ash

Oxides	% By mass
SiO_2 as silica	54.78
Al_2O_3 as alumina	23.52
Fe_2O_3 as ferric oxide	08.90
CaO as calcium oxide	02.10
MgO as magnesium oxide	01.30
K_2O as potassium oxide	00.72
SO_3 as sulfur trioxide	00.63
Na_2O as sodium oxide	00.33
Loss of ignition	01.61

Table 2 General property of metalized plastic films

Property	Values	Unit
Resin category	Polypropylene	–
Plastic type	LDPE	–
Density range	0.925–0.94	g/cm^3
Thickness	0.08	mm
Water vapor resistance	Good	–
Oxygen permeability	High	–
Tensile strength (tested)	800	N/mm^2
Elongation	8–10	%
Co-efficient of friction	0.45–0.55	–
Metalized layer material	Aluminum	–

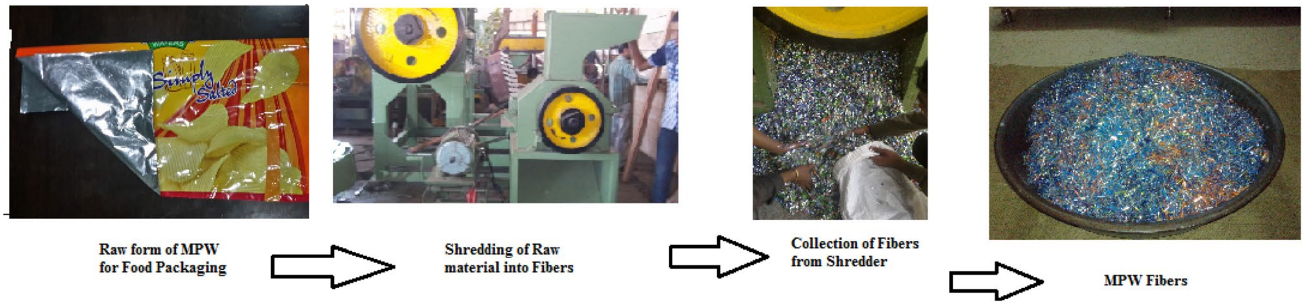


Fig. 1 Process of obtaining MPW fibers

Table 3 Mix proportion of constituents for GPC mixes

Designation	Liquid-fly ash ratio	Oxides ratio	Sodium content	NS–NH ratio	SP	Water	20 mm aggregates	10 mm aggregates	Sand	Fly ash	MPW
Unit			Molar (M)		%	%	kg	kg	kg	kg	% (kg)
GPC0	0.5	2.25	16	2	0.5	10	443.52	850	554	368	0.0 (0)
GPC0.5	0.5	2.25	16	2	0.5	10	443.52	850	554	368	0.5 (4.5)
GPC1.0	0.5	2.25	16	2	0.5	10	443.52	850	554	368	1.0 (9.2)
GPC1.5	0.5	2.25	16	2	0.5	10	443.52	850	554	368	1.5 (14)
GPC2.0	0.5	2.25	16	2	0.5	10	443.52	850	554	368	2.0 (18.5)

for each type of test for the hardened GPC. The cube specimens were used to obtain compressive strength response. The cylinders were used to determine the splitting tensile strength and the beam specimens were utilized to study the flexure behavior of the hardened GPC. The disk specimens were used for obtaining the impact resistance response of the mixes. The beam specimens were heat cured in a steam bath facility and other specimens were given the oven curing. All the specimens were heat cured for 24-h time duration.

Tests for workability

The freshly mixed GPC for all batches were tested for workability by conducting the slump and compaction factor tests according to the guidelines of IS: 1199–1959 [34]. The results of the slump test exhibit the consistency of the mix. Though the slump test does not include the effects of all the parameters affecting workability of a mix, satisfactory information about the uniformity of the constituents can be studied from the test results. The degree of compaction of the fresh modified GPC was assessed by conducting the compaction factor test.

Tests for strength properties

Compressive strength and splitting tensile strength of the modified GPC was determined by subjecting the specimens to an axial compressive force. The tests were conducted at compression testing machine of 2000 kN capacity according to the IS: 516–1959 [35]. The two-point loading flexure test was performed on the beam specimens at the Universal testing machine of 400 kN capacity conforming to the IS: 516–1959. Resistance to the impact load was determined by the drop weight hammer test. The apparatus was developed at the laboratory as per the guidelines of the committee recommendations by ACI 544 [36].

Sustainability analysis of modified GPC

A study of the sustainability attributes of the MPW and modified GPC mixes was performed including the energy requirements and cost involved in the production of GPC. The comparison also included the impact of food packaging wastes on the environment when dumped into the landfill and being present into the surrounding for a long time.

Results and discussion

Workability response

Figure 2 shows response of fresh GPC mixes to the addition of MPW fibers for varying fractions on the consistency. From the results, it was evident that the inclusion of MPW

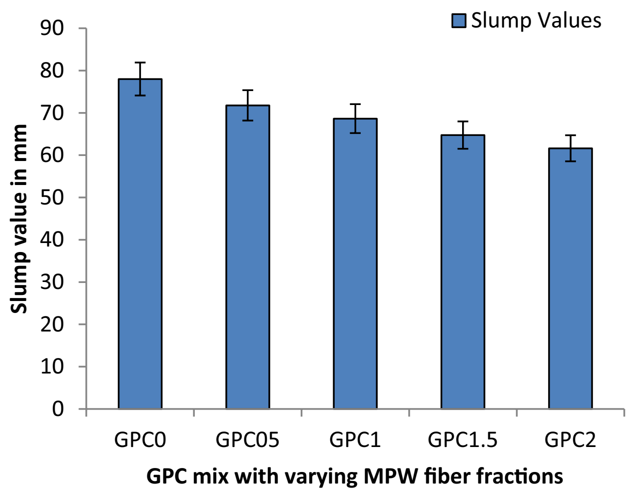


Fig. 2 Effect of MPW fibers in slump response

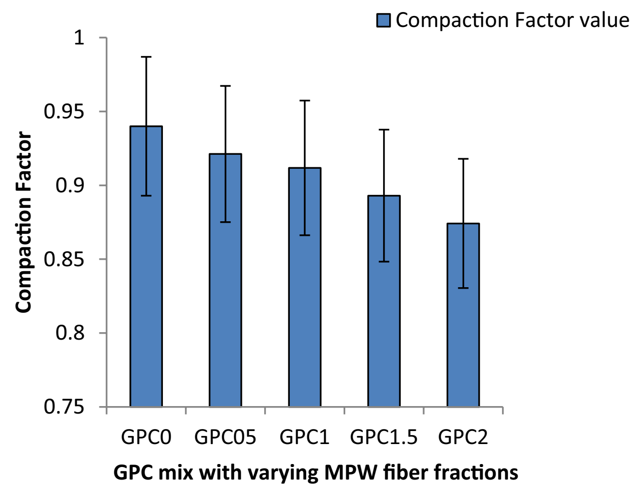


Fig. 3 Effect of addition of MPW on compaction factor response for GPC mixes

fibers reduces the flow and consistency of the mix. The reduction was negligible, however, at the lower dosage of MPW fibers namely 1% by volume of the mix.

The response can be explained by observing the formation of a mesh-like the macrostructure of the fibers around the constituents of GPC. The fibers due to the larger surface area acquired the adherence to the aggregates [23]. Moreover, the gel formation by alkali solution and fly ash was affected by the presence of the MPW fibers. This is due to the macro-size of the fibers and geometric parameters of the fibers. Similar response by the other researchers worked with fibers into the GPC is reported [32]. However, it is also observed by the authors during the study [6, 7] that lower dosage of MPW fibers namely 0.5% and 1% by volume of the mix, showed insignificant alteration of the fresh behavior of the mixes. This may be due to the reason of the total volume of the fibers was relatively less in the matrix of the mix compared to the other constituents. Sufficient gel formation and desirable mixing were found possible at such a low dosage and could not affect the consistency effectively. However, with the increase of MPE fiber fractions, the viscosity of the mix reduced and the balling effect in the matrix was significantly higher and resulted in reduced workability. For a workable concrete for normal conditions, the slump values ranging from 70 to 150 mm is recommended. The slump exhibited by the GPC0 mixes was 78 mm and showed mild to moderate reduction with increased dosage of MPW fibers up to 62 mm, up to 1% MPW fibers the GPC mixes maintained slump of 70 mm with fair enough workability. The associated values of the compaction factor to the standard slump values of concrete ranges between 0.92 and 0.96 as per the usage for normal concreting. The compaction factor for GPC0 and modified GPC mixes varied from 0.94 to 0.87, respectively, with the addition of the MPW fibers. The test results showed that the compaction factor reduced from 0.94 to 0.91 for the inclusion of 1% of MPW fibers and the modified mix was found within the acceptable range of test values.

The results shown in Fig. 3 exhibit reduced trend of increment of compaction factor. The compaction factor exhibits the pore structure and compressibility of the fresh mix in general. From the test results it may be noticed that the presence of fibers can alter this property for the degree of compaction. As the MPW fibers are macro-fibers the response obtained was not significant as far as the microstructure of the concrete is concerned. The macro-fibers tend to alter the viscosity as a primary effect and largely contribute to the consistency. This response was evident from the slump test results.

As the results of compaction factor shows, the compressibility is not significantly affected by the MPW fibers. This may be due to the high compressibility of the MPW fibers. As observed by the authors in their past research [6], the MPW fibers are hydrophobic and lightweight compared to the other constituents. Though the flow of a fresh mix is interrupted by the MPW fibers, they do not obstruct the compaction process of the mix. Therefore, the ratio of non-compacted to a fully compacted fresh GPC is not significantly affected and shows a gentle reduction. However, the increased dosage of MPW fibers results in a mesh-like structure where the material segregation takes place and the compaction process does not meet to the desirable level. This response can be seen from the results shown in Fig. 3.

The addition of MPW fibers also reduced the density of the conventional GPC as shown in Fig. 4. With the increase fraction of MPW fibers, the density reduced with 2%, 3%, 5% and 7% for the 0.5%, 1%, 1.5% and 2% fraction of MPW fibers, respectively. Though the alteration is not significant,

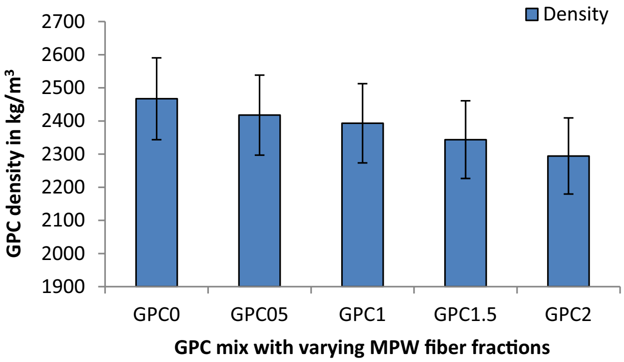


Fig. 4 Effect of MPW fiber addition on density of GPC mixes

it is interesting to note that with further research on the inclusion of MPW fibers on fresh properties at microstructural attributes, there may be potential with MPW fiber for preparing the lightweight GPC mixes.

Compressive strength

The past researchers have noticed that generally the compressive strength of GPC is not affected significantly by the fibers [27]. In the present study, the compressive strength reduced from 41 to 38 MPa for the increment of MPW fibers from 0 to 2%. The compressive strength of hardened GPC reduced with the fraction addition of MPW fibers from 0.5 to 2% in the range of 2–7% at every 0.5% fractional increments of fibers. The response is shown in Fig. 5. Addition of MPW fibers in GPC did not affect the strength-gaining mechanism of the constituents. This is due to the fact that the MPW fibers are highly chemical resistant and do not participate in the polymerization process required to form the geopolymer binders. It is an important observation that shows the feasibility and level of utilization potential of MPW fibers in GPC. It can be noticed that the MPW fibers do not reduce the strength of GPC in compression adversely. This means the addition of MPW fibers may be effective from the sustainability perspective and in a way where the primary strength properties are not compromised. Moreover, the addition of MPW fiber with 1% volume fraction reduced the strength merely by 3%. This response by the specimens containing MPW fibers ensures the feasibility of the addition of MPW fibers in GPC.

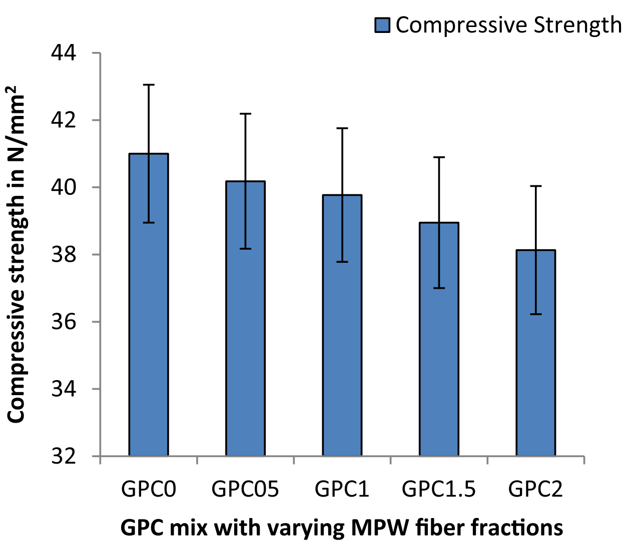


Fig. 5 Effect of MPW fibers on compressive strength of GPC mixes

The study of the failed specimens containing MPW fibers showed interesting behavior during and post-failure stages. Unlike reference specimens of GPC, the specimens with MPW fibers showed good resistance to the cracking of hardened concrete. As shown in Fig. 6, the fibers did not allow the wide crack formation in the specimens at varying stages of load application and hold the mass of concrete together. Though the observation was a visual fact and no microstructural study was carried out, the role of MPW fibers to the cracking response was found significant. The failed specimens containing MPW fibers did not show complete separation of the material at the peak load values and exhibited good resistance to the catastrophic failure of the GPC.

Splitting tensile strength

Resistance to the splitting action can be determined by conducting splitting tensile strength test on cylinder specimens. The response by modified GPC specimens subjected to the splitting action was obtained as shown in Fig. 7. As a general response, the splitting tensile strength of the GPC specimens ranges from 3 to 4 MPa, without fibers and with fibers the values improves significantly as observed by the other researchers [27]. Primarily the role of the fibers in hardened

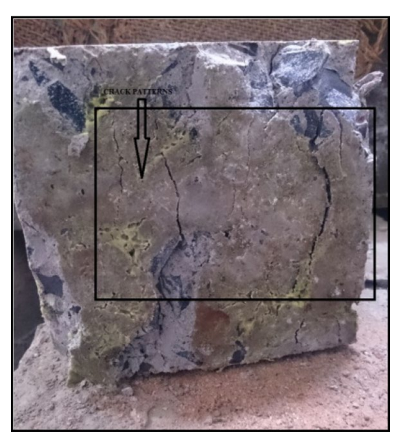


Fig. 6 Failure pattern on cube specimens tested for compressive strength

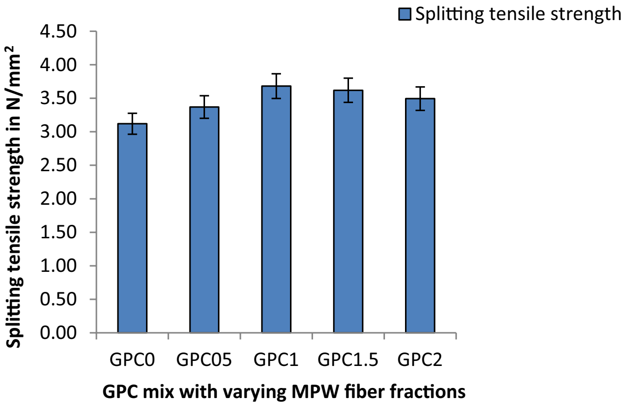
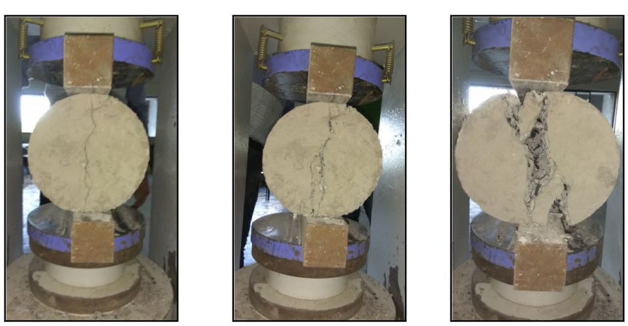


Fig. 7 Effect of MPW fibers on splitting tensile strength of GPC

concrete is to abridge the cracking phenomenon [13]. The cracks generated at micro- or macrolevel irrespective to the causes are resisted by the adherence capacity of the hydrated cement paste or the hardened binder solution in case of geopolymer-based concretes [22]. The fiber tends to adhere to the hardened gel structure as well as to the aggregates at the transition zone as observed by other researchers [8]. The presence of fibers resists the crack formation and especially the crack propagation by discontinuing the cracking path within the hardened concrete. This response by fibers is commonly seen for geopolymer as well as cementitious concrete. The MPW fibers also contributed in a similar way as in case of other types of recycled fibers and contributed to the reduced cracking due to the splitting actions on the specimens [25].

The addition of the MPW fibers increased the splitting action in the range of 8%, 18%, 16% and 12% for the increment of the MPE fiber dosage from 0.5 to 2%. The highest increment of the resistance was noticed at 1% volume fraction. As shown in Fig. 8, the specimens failed at the initial and final failure stages, demonstrated the improved resistance to the splitting action. The higher dosage of MPW fiber did not effectively increase the resistance. This may be explained as the concentration of fibers in the mesh-like structure with GPC constituents rather reduced the resistance gently. A similar trend of reduced resistance is observed by the authors in case of cement concrete [13]. Importantly, even at the highest dosage of MPW fibers, the specimens of modified GPC with MPW fibers showed excellent improvement compared to the specimens of reference GPC. The test exhibited an advantageous inclusion of MPW fibers in GPC mixes.



(a) First crack **(b)** Intermediate failure **(c)** Final failure

Fig. 8 Crack patterns on GPC specimens tested for splitting tensile strength

Flexure strength

Flexure strength test is one of the indirect measures of the tensile strength or resistance by the hardened concrete. The beam specimens were prepared with varying MPW fibers mixed into the GPC. The test results are shown in Fig. 9. The addition of MPE fibers into the GPC increased the flexure resistance and the trend was found to be similar to that of observed for the splitting tensile strength tests. The flexure strength increased in the range of 4%, 10%, 9% and 7% for the MPW fiber fraction from 0.5 to 2%, respectively. It is observed that the flexure strength of the hardened concrete is primarily depended on to the compressive strength of the mix. In this regard, a good agreement to the relationship between compressive strength and flexure strength with the MPW fibers was observed. The normal range of the flexure strength of GPC is observed to be 2.5–4 MPa without fibers. However, the test results showed that for the addition of MPW fibers improved the flexure strength up to 4 MPa and showed the potential of MPW fibers in the GPC mixes.

The presence of MPW fibers in GPC increased the load carrying capacity of the modified GPC also. The phenomenon was studied by relating the load with the deflection of the member. The behavior of each specimen as the average of three specimens is presented in Fig. 10. The MPW fibers

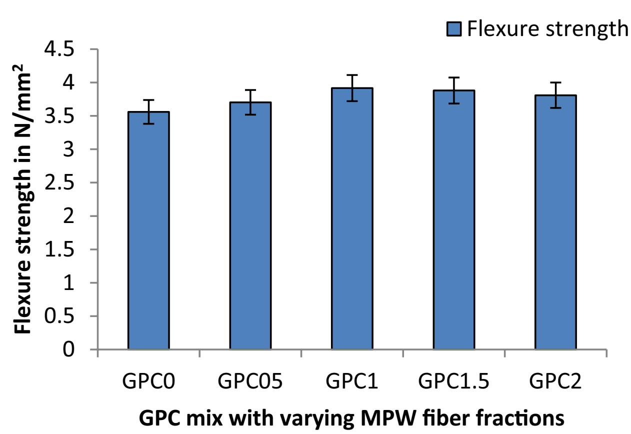


Fig. 9 Effect of MPW fibers on flexure strength of GPC

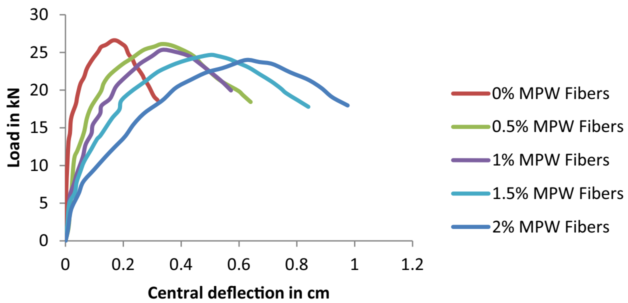


Fig. 10 Effect of MPW fibers on load–deflection relationship for GPC

contributed to the resistance of the hardened concrete under the flexure action by improving the cracking resistance. As the cracking in the GPC beam specimens reduced, the load carrying capacity improved. Though the failure of the members subjected to the flexure was not ductile or elastic, the MPW fibers were found capable of delaying the final failure of the specimens at a given load compared to the reference GPC specimens. This response is noticed by developing the graphs showing the load–deflection relationship for varying MPW fibers fractions in the GPC as shown in Fig. 10. A careful observation of the failed specimens showed that the MPW fibers could get good capture within the hardened GPC mass. As shown in Fig. 11, the MPW fibers were effectively held by the hardened gel of the alkali binders. The lumps collected from the failed specimens also demonstrated the phenomenon. However, the exact mechanism of gripping of MPW fibers into the GPC requires further detailed investigations and the authors are currently working on it.

On relating the strength properties namely splitting tensile strength and flexure strength of GPC specimens, it was observed that the relationship is linear by nature and the strength properties can be mapped proportionately to obtain the effect of the addition of MPW fibers into the concrete. Both the properties exhibit the resistance to cracking due to the presence of the MPW fibers and the interrelationship of the two showed good agreement also as shown in Fig. 12. The purpose of obtaining interrelationship of the properties is referred to validate the experimental results. It was observed that the effect and role of MPW fibers in GPC remained similar as far as the cracking resistance of the mass is concerned for different load and deformation conditions.

Impact resistance

Impact load causes surface damage of the hardened concrete through the cracks along the radial and axial direction of the load within the specimens. The load causes stress concentration at the surface of the specimen and according to the resistance capacity of the specimens, the stresses are distributed within the mass. The better is the response when the concrete is with better strength. As observed from the

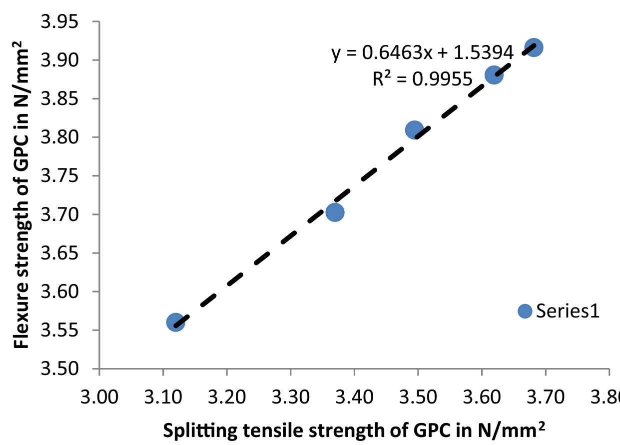
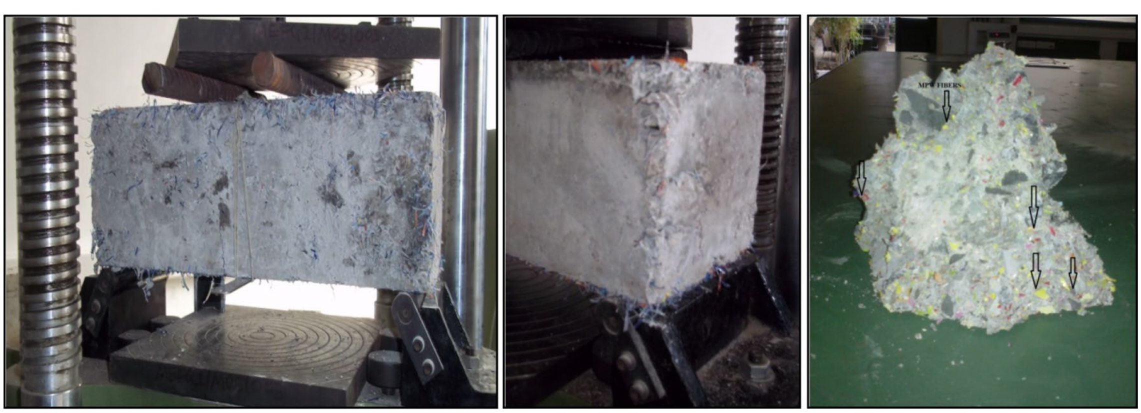


Fig. 12 Relationship between the splitting tensile strength and flexure strength



(a) Beam with initial crack **(b)** MPW in specimens **(c)** Lump of specimen

Fig. 11 MPW fibers in GPC-tested flexure specimens compressive and splitting tensile strength tests, the addition of MPW fibers into the GPC improved the strength at a given fraction dosage. A nearly similar response by the modified GPC specimen was obtained by conducting the impact load test. The results are shown in Figs. 13 and 14 for the initial and final cracking stages, respectively.

The resistance to the impact was increased by 13%, 17%, 15% and 12% with respect to the reference GPC for the addition of MPW fibers with 0.5–2% volume fractions. A similar trend is observed by the other researchers that the inclusion of short PVA fibers was capable to improve the impact strength of GPC. The maximum response was obtained at the addition of 1% MPW fibers. The resistance was recorded at two different stages. As shown in Fig. 13, the number of blows required to cause initial cracks in the specimens were recorded. Figure 14 shows the number of blows required to cause final failure of the specimens with varying MPW fibers. Based on the number of blows required to cause initial and final failure, the blows were converted to the energy absorbed by the GPC specimens was obtained according to the guidelines of ACI 544 recommendations. The following equation was used for calculating the energy absorbed during the impact load test by the specimens and utilized to determine the ductility index for the GPC mixes due to the addition of MPW fibers.

$$\text{Eimpact} = m \times g \times h \times N,$$

where E_{impact} is the energy in Joules, m is the hammer mass in kg, g is the gravitational acceleration constant (9.81 kg / s^2), h is the height of the fall of hammer (450 mm), and N is the blow count.

Table 4 shows the ductility index determined for each batch of the GPC mix for varying fractions of MPE fibers. The ductility index is a ratio of the energy values causing

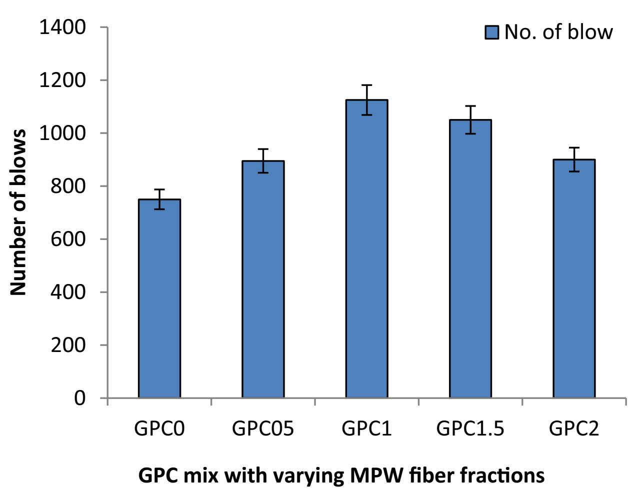


Fig. 13 Effect of MPW fibers on impact resistance from GPC (initial cracking)

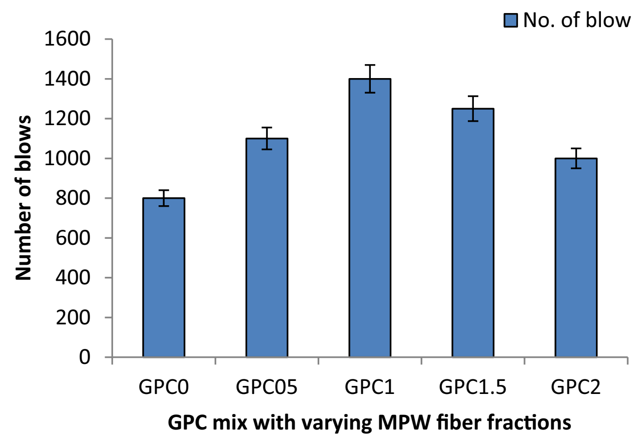


Fig. 14 Effect of MPW fibers on impact resistance from GPC (final cracking)

final failure to the initial failure of the GPC specimens. It was observed that the addition of MPW fibers increased the ductility index of the GPC specimens. The addition of 1% of the MPW fibers increased ductility by 15%. However, the typical trend of reduced rate of increment in the impact resistance and ductility was noticed with increased dosage of MPW fibers.

The role of the fibers was to hold the concrete and effectively distribute the stresses within the hardened GPC mass. The fibers reduced the formation of wide cracks at the surface and contributed to the less damage on the surface. This response was observed from the patterns developed on the specimens at the initial and final failure stages. As shown in Fig. 15 the cracking and failure patterns exhibited the cracking resistance capacity of the MPW fibers within the hardened GPC mass. The results ensured the effectiveness of the addition of MPW fibers into the GPC as the resistance to the impact was increased due to the presence of the MPW fibers.

Table 4 Ductility index for GPC specimens with varying MPW fiber fractions

GPC batch	MPW fibers fraction	Energy absorbed initial cracking (J_i)	Energy absorbed final cracking (J_f)	Ductility index (J_f/J_i)
	%	*J*	*J*	
GPC0	0	14,899	15,892	1.07
GPC05	0.5	17,779	21,852	1.23
GPC1	1	22,348	27,811	1.24
GPC1.5	1.5	20,859	24,832	1.19
GPC2	2	17,879	19,865	1.11

(a) Disk specimen **(b)** Cracking patterns of tested specimens under impact loading

Fig. 15 Cracking pattern on the specimens subjected to impact load

Sustainability analysis of modified GPC with MPW fibers

Environmental concerns of MPW

The impacts of generation of wastes by numerous post-consumer activities related to the packaged foods are reported by researchers and organizations [1]. The scenario of pollution and challenges of management for MPW are required to be studied with the context of the environmental impact assessment (EIA) including the life cycle assessment of MPW generated by the refused wastes of food packaging. Moreover, the life cycle assessment can be carried out for clarifying the advantages expected from the novel modified GPC mixes containing MPW fibers.

Many of the plastic wastes are recyclable and can be repeatedly used by appropriate recycling techniques [2]. However, the metalized plastic wastes are largely unfit for recycling and not appropriate for reuse due to following major obstacles:

- The lack of proper method and awareness of the first refusal of MPW by the consumers and industries, make the collection and separation of MPW difficult.
- The MPW is not safe for incineration as they do not melt and get immediately burn out without any residues, therefore, the negligible recycled material is received. Moreover, the burning of MPW generates toxic chemicals into the air.
- The MPW dumped into the landfill are durable and highly chemical resistant for natural degradation.
- With the context of social-economical advantages, the collection or manual separation of MPW is largely neglected [33] being a non-profit or not worthy repaying activity.

The concept of the life cycle assessment of MPW

From the stage at production to the refusal, the MPW is highly energy intensive. Starting to end, at every instance, the metalized plastic and the waste resulting from them demand energy and release pollution to the surroundings. Both the sides namely the production and the waste disposal treatments consume energy and emit hazardous residues and by-products. The illustration of Fig. 16 shows the life cycle assessment attributes of MPW. It can be observed that even the end of life for MPW is a never-ending process. The assessment exhibits that even the final disposal of MPW continues to create pollution and hazards to the surroundings. This is mainly due to the high chemical resistance and durability of MPW for natural degradation process. Therefore, the severity of MPW generation requires the attention of the researchers for its sustainable usage. Addition of MPW into the GPC may lead to the preparation of potentially green construction material. However, the assessment of MPW discussed in the present study is a simple and broad analysis only and used for supporting the feasibility of MPW into the GPC perspective.

Concept of life cycle assessment of preparing GPC with MPW

Utilizing MPW as a filler or fibrous material into the GPC encourages the following advantages from the perspective of the environment, social and economic attributes:

- The process of obtaining fibers from MPW does not require any intense recycling treatment. A typical plastic waste recycling is much more energy intensive compared to the simple mechanical shredding of MPW.
- Landfill of MPW articles may not be the final disposal. The MPW even after a long time remain present in land

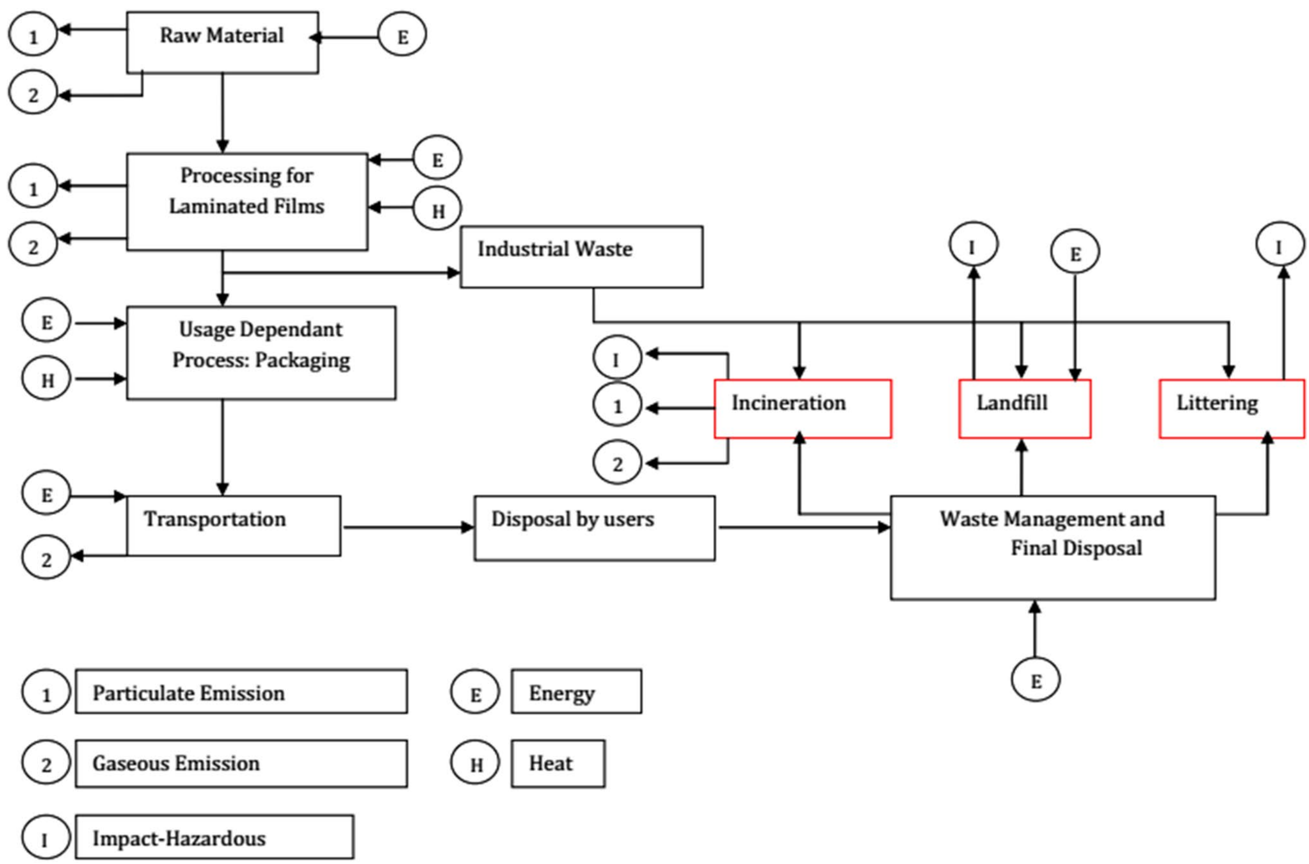


Fig. 16 Illustration of LCA of MPW

and water streams in microform as they are strongly chemical resistant and non-biodegradable. Therefore, a lifelong threat of pollution continues endlessly by MPW.

- Addition of MPW in GPC in fiber form contributes to the strength enhancement, especially for effective cracking resistance.
- MPW fibers are chemically nonreactive and may contribute to the durability enhancement of GPC. It is to be noted that the full-length durability study on GPC containing MPW fibers is ongoing by the authors and the pilot studies are about to receive in near future.

The assessments presented in Figs. 16 and 17 may be a guideline for obtaining the clear advantages of the utilization of MPW in GPC. Though the addition of MPW fibers does not replace any of the conventional constituents of the GPC mixes, it would be worth to note that the presence of the MPW fibers can effectively contribute to the strength improvement. Moreover, the MPW fibers were not treated for any conditioning except simple cleaning with water and mechanical shredding before the usage.

Applications and usages of the GPC containing MPW fibers

The GPC resembles cement-based concrete for the practical applications. Researchers have utilized GPC for strengthening of conventional reinforced concrete members [37], preparing bricks for construction [38] and in the production of the precast construction elements such as sewer pipes [39], preparing the pavement surfaces [40]. The proposed GPC containing MPW fibers can be utilized for preparing the pavements, bricks and small to medium scale precast elements not subjected to the heavy structural loads as the primary stage of application to the construction field. The tests results exhibited that the conventional GPC can be upgraded for better splitting tensile resistance and improved flexure resistance. This response encourages the usage of GPC containing MPW fibers for the usage in preparing structural members conventionally prepared by reinforced concrete after the ample experimental studies.

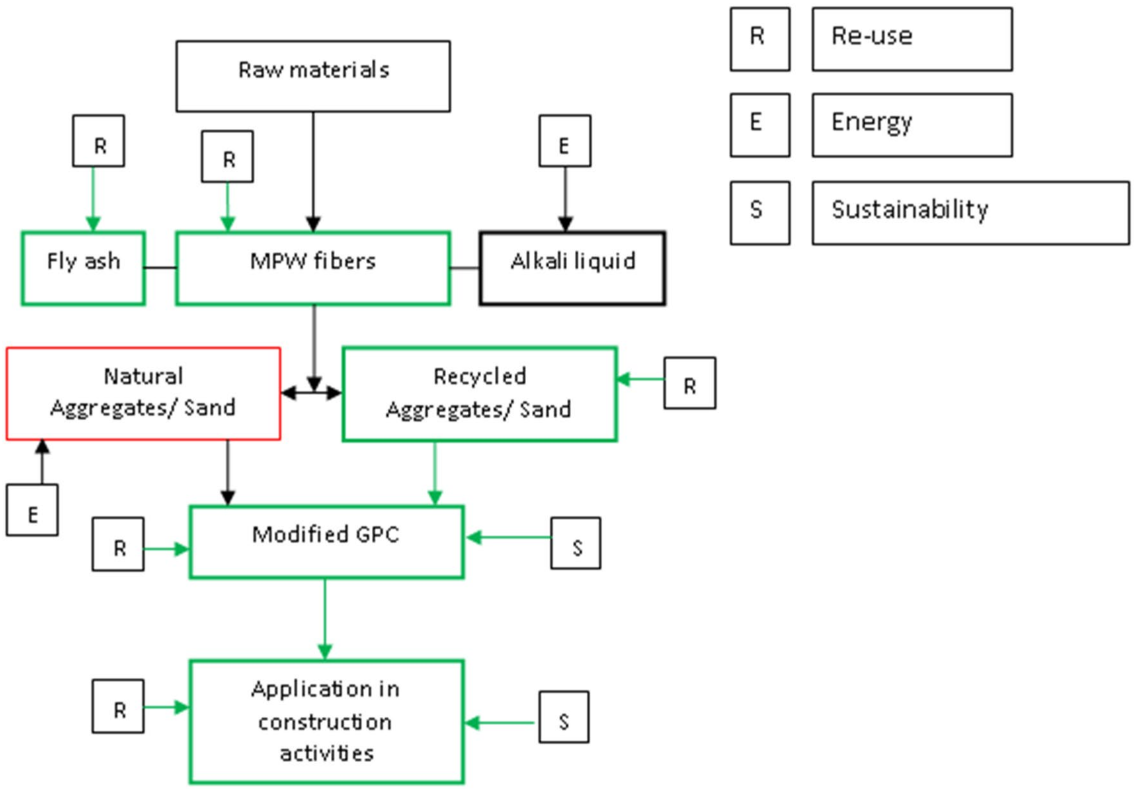


Fig. 17 Illustration of LCA of GPC modified with MPW

Conclusion

The experimental study of GPC containing varying fractions of MPW fibers exhibited potential of MPW utilization in fiber form with following noticeable findings:

- The addition of MPW in fiber form showed excellent improvement up to 18% and 10% in the resistance to the splitting actions and flexural actions at the dosage of 1% by volume fraction in the specimens. The addition of MPW fibers improved the load carrying capacity of the reference GPC for a given loading.
- The MPW fibers found capable of resisting the formation of wide cracks at the final stage of failure of the specimens subjected to the impact loads and enhanced the ductility of the GPC mixes.
- The LCA of MPW showed that the metalized plastics are one of the long-lasting factors responsible for the adverse impacts on the environment. Therefore, a sustainable utilization of MPW was found desirable.
- The process of preparing GPC with MPW by the LCA method exhibited the advantages of such a novel combination for availing the dual advantage of improved strength and alternate way of disposal of MPW to mitigate the pollution.
- For all test conditions, the 1% volume fraction of the MPW fibers was found optimum and demonstrated the potential toward utilization of MPW fibers in GPC mixes.

Acknowledgements The authors are thankful to the Marwadi University for facilitating the sources of the raw materials and testing laboratory facilities. The authors also acknowledge the support by the industrial packaging unit “Umiya Plastics” located at *Shapar*—an industrial area near Rajkot city for providing MPW. The authors are thankful to the colleagues, students, and staff of the Department of Civil Engineering at Marwadi University for their help and contribution to the experimental program.

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